ICARUS and the status of LAr technology

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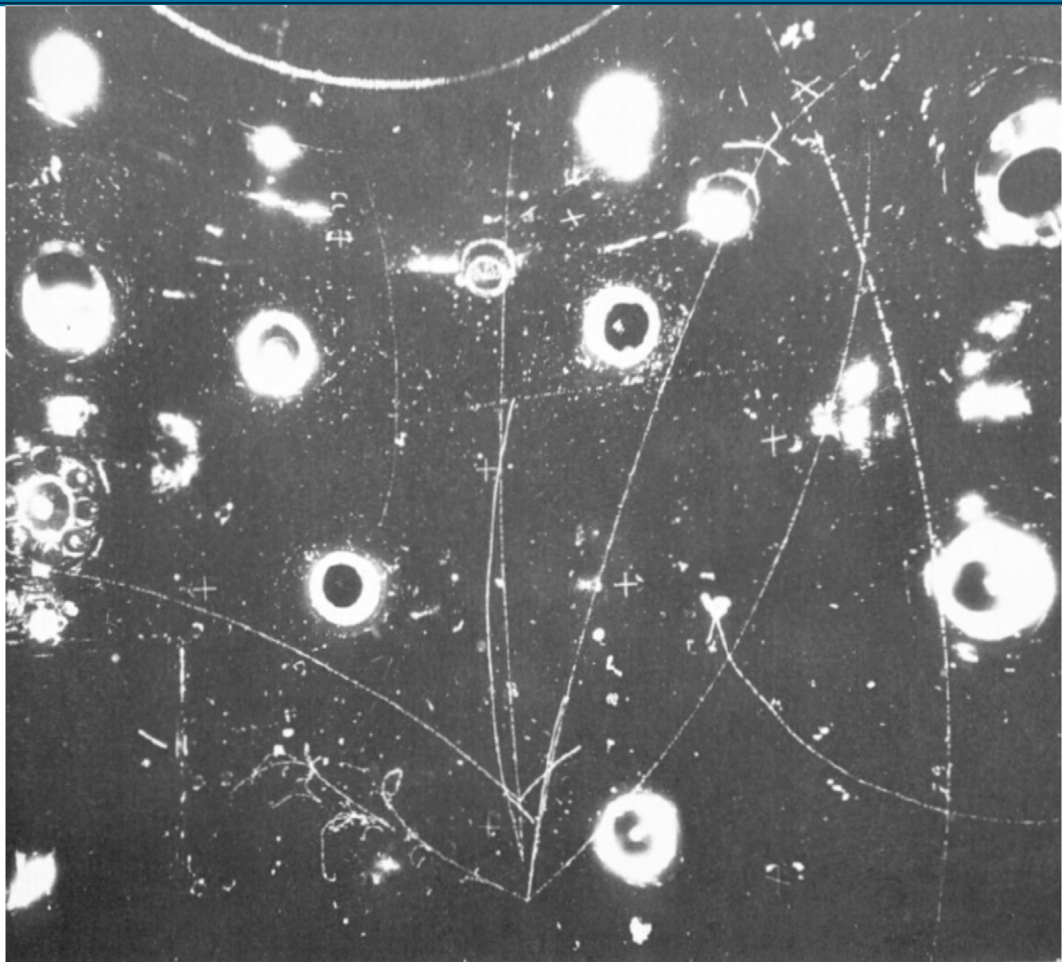
History of imaging: a Gargamelle neutrino event



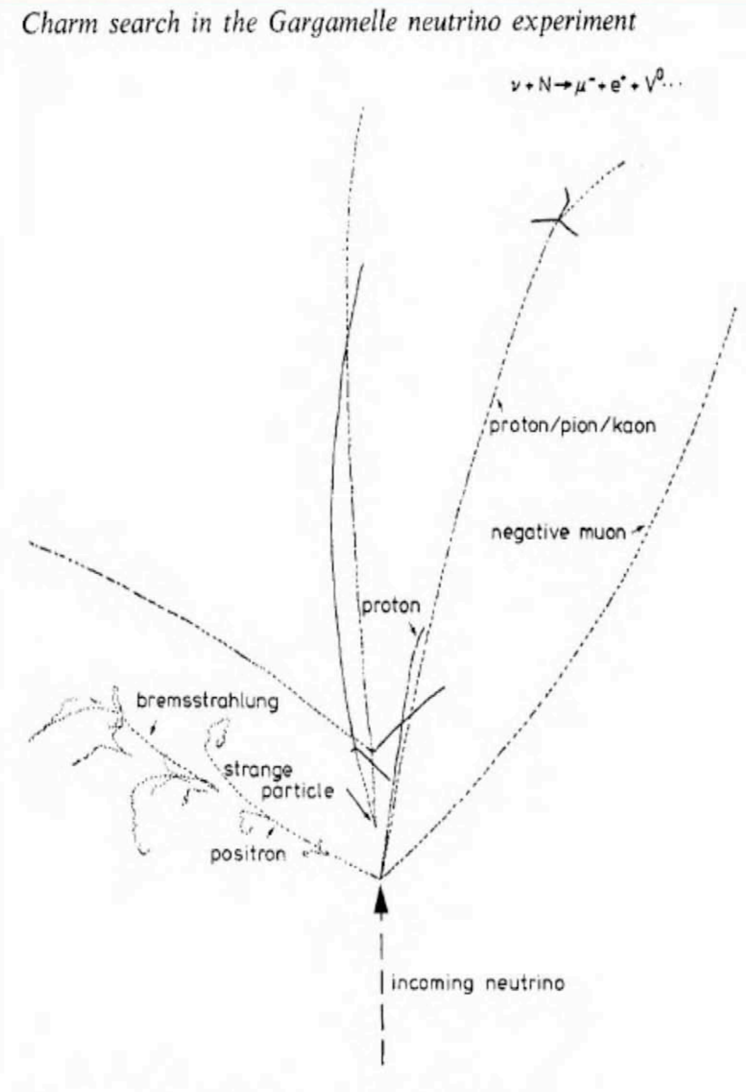
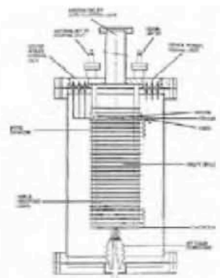


Figure 1. (*b*) Sketch of the event shown in figure 1(*a*).

Charm production in a neutrino interaction
The total visible energy is 3.58 GeV.

The path to massive liquid Argon detectors



24 cm drift wires chamber

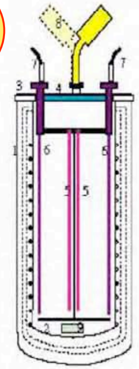
CERN

1

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

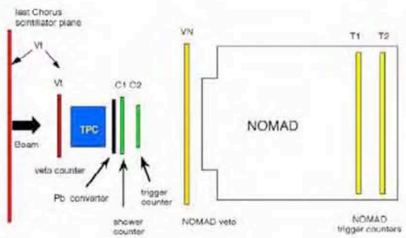
3 ton prototype



1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

Laboratory work



50 litres prototype
1.4 m drift chamber

CERN

3

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

T600 detector

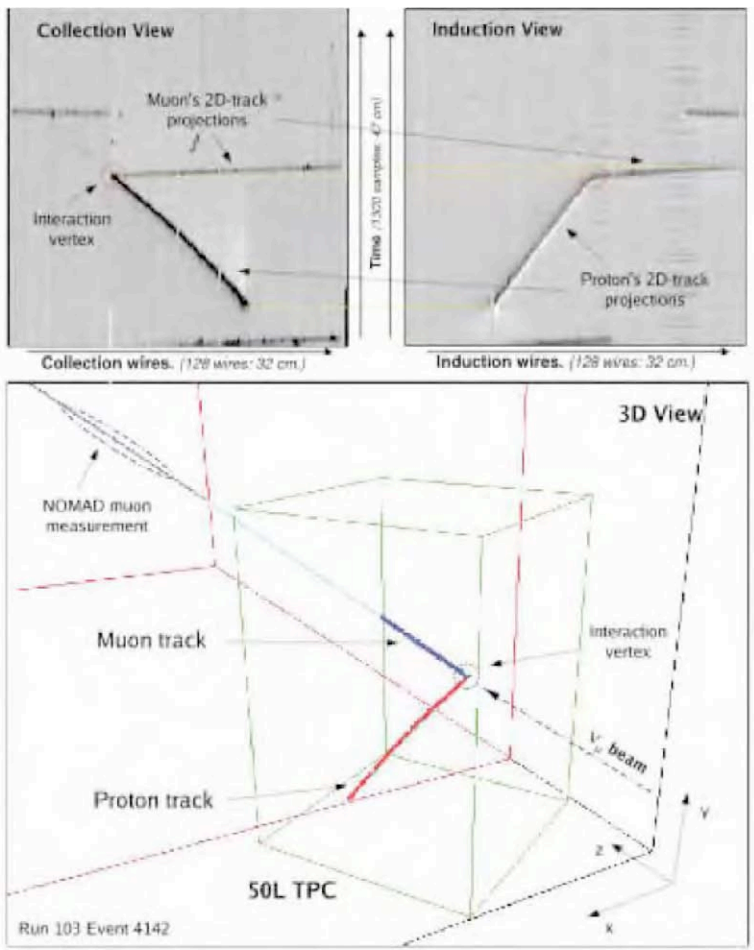
2001: First T600 module

5

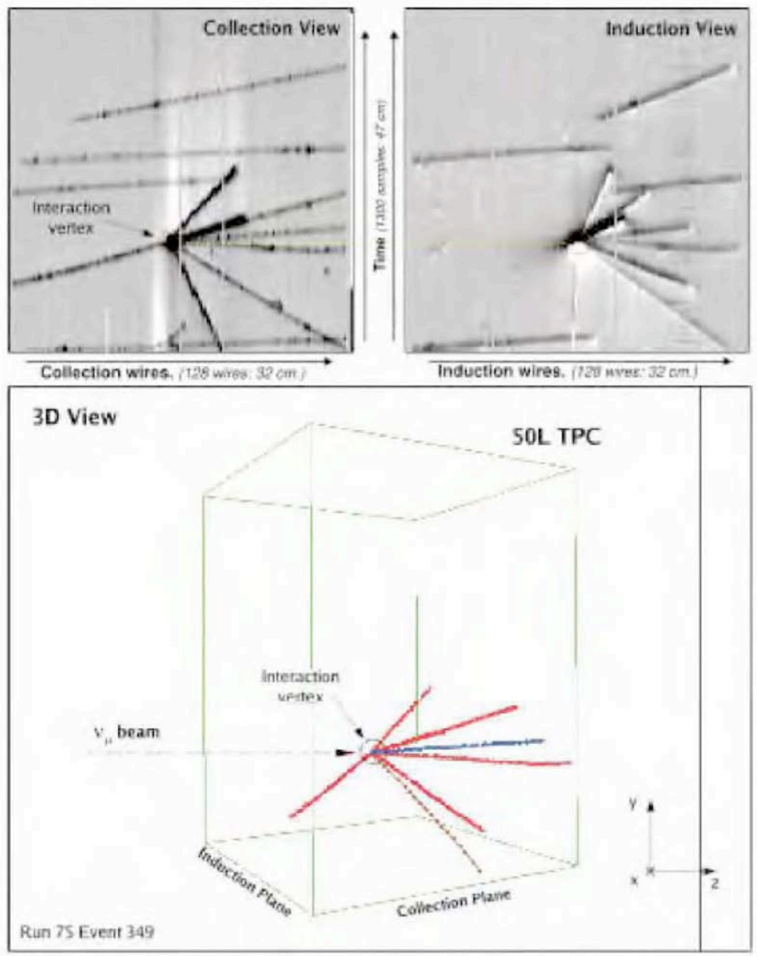
Cooperation with industry

Early neutrino physics at CERN_WANF(1997-98)

- Quasi-elastic events with a 50 litres LAr TPC in front of NOMAD:
  - a quasi-elastic neutrino event;
  - a multi-prong neutrino event reconstructed in 3D



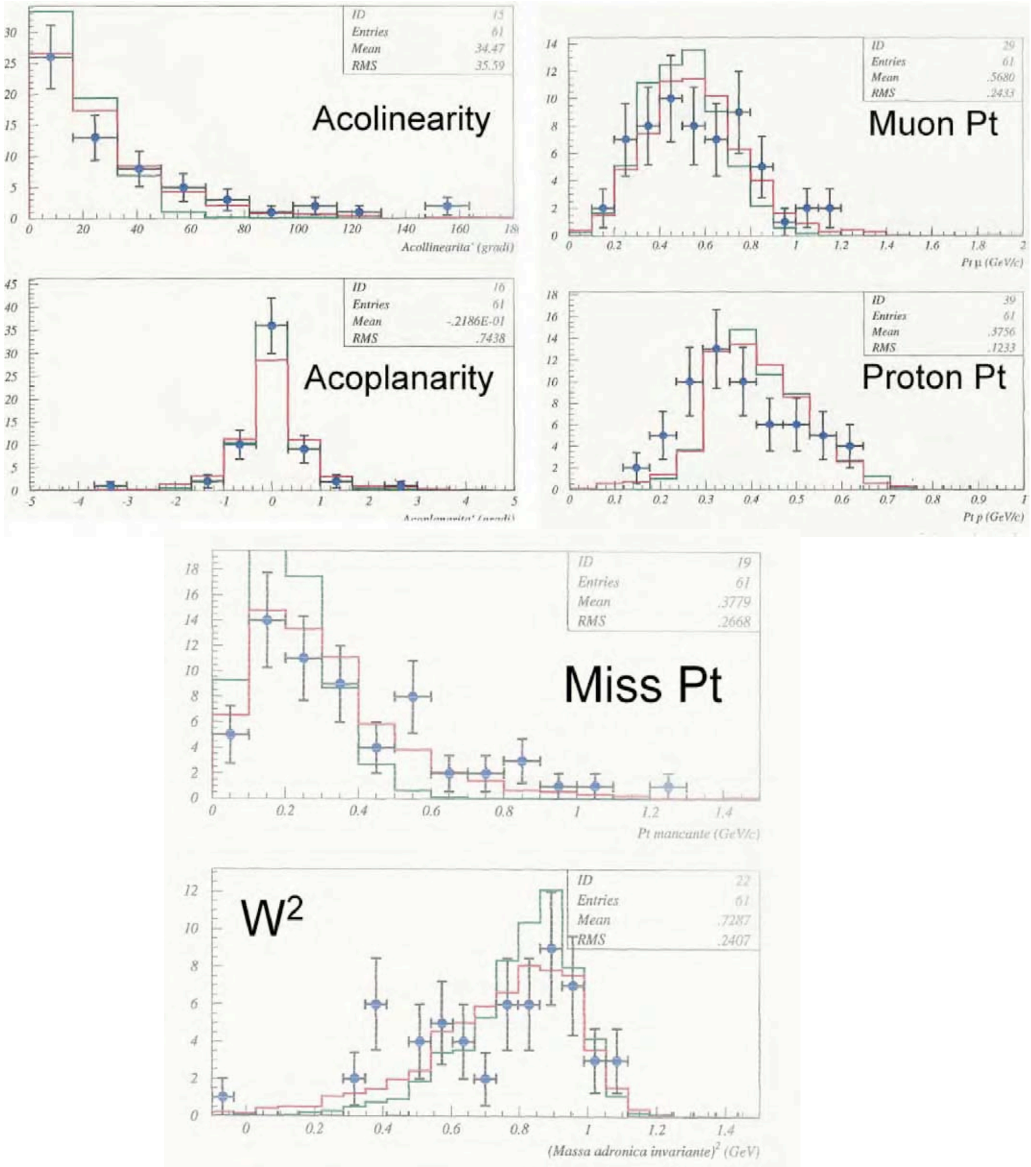
(A)



(B)

Reconstruction of Quasi-elastic LAr events

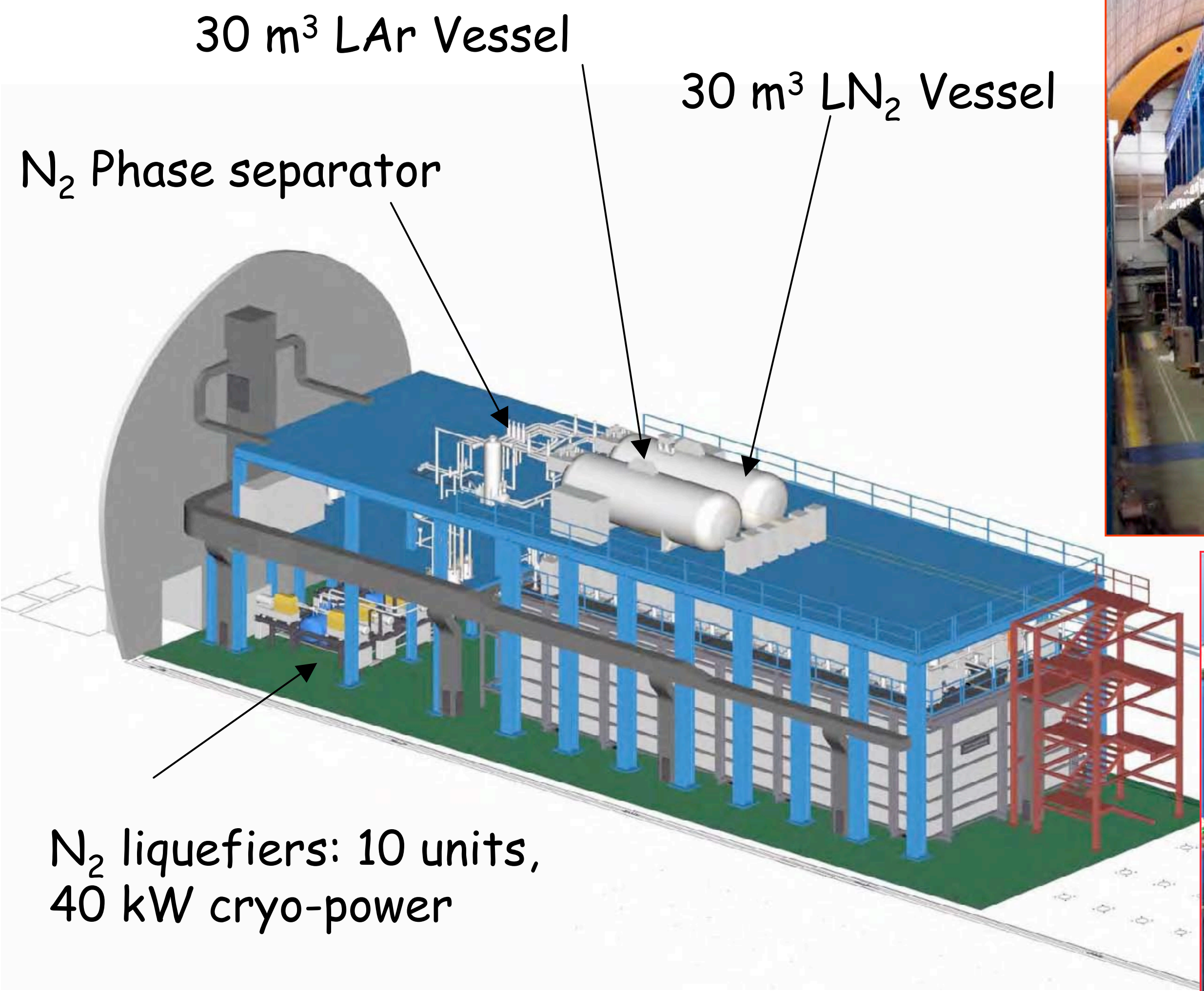
- Quasi-elastic neutrino events in LAr have been reconstructed in the 50 litre ICARUS LAr-TPC exposed to the CERN-WANF beam in coincidence with the NOMAD experiment.
- Simulations, accounting for Nuclear Fermi motion and re-interactions in nuclei, are found in good agreement with a 200 pure lepton-proton final state events with 1 proton TP > 50 MeV (range > 2 cm) and any number protons TP< 50 MeV.



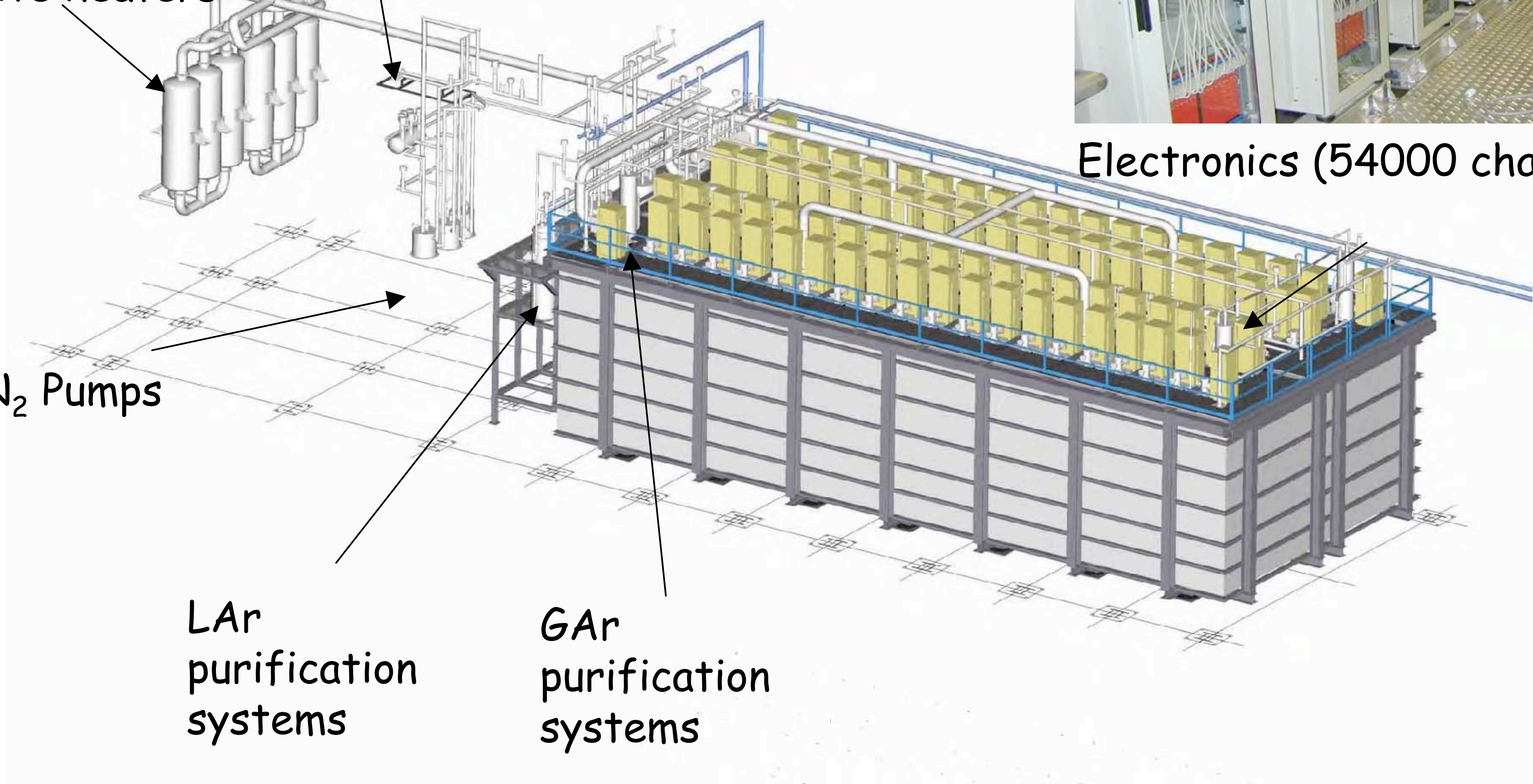
ICARUS (CNGS2): the first large scale LAr experiment

- ICARUS represents a major milestone in the practical realization of a large scale LAr detector. Successfully operated on surface in Pavia in 2002, it is now operational in the underground HallB of LNGS.
- The T600 at LNGS will collect simultaneously "bubble chamber like" neutrino events events of different nature
- Cosmic ray events
  - ≈ 80 ev/year of unbiased atmospheric CC neutrinos.
  - Solar neutrino electron rates >5 MeV.
  - Supernovae neutrinos.
  - A zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.
- CERN beam associated events: 1200 ν_μ CC ev/y and 7-8 ν_e CC ev/year
  - Observation of neu-tau events in the electron channel (with sensitivity comparable to OPERA
  - A search fo sterile neutrinos
- After CNGS2 runs during 2011 and 2012, the "next step" is a proposed search of sterile neutrinos with the CERN PS beam.

ICARUS T600 in LNGS Hall B

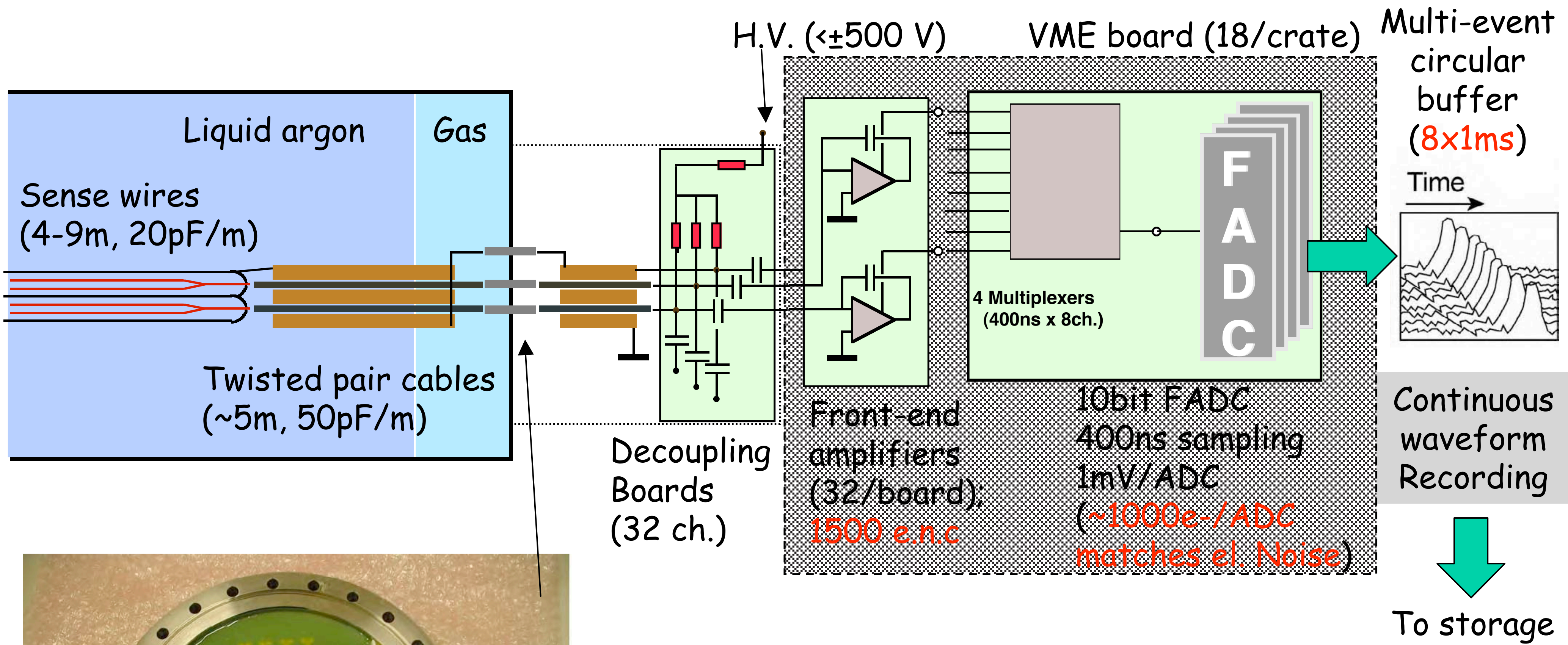


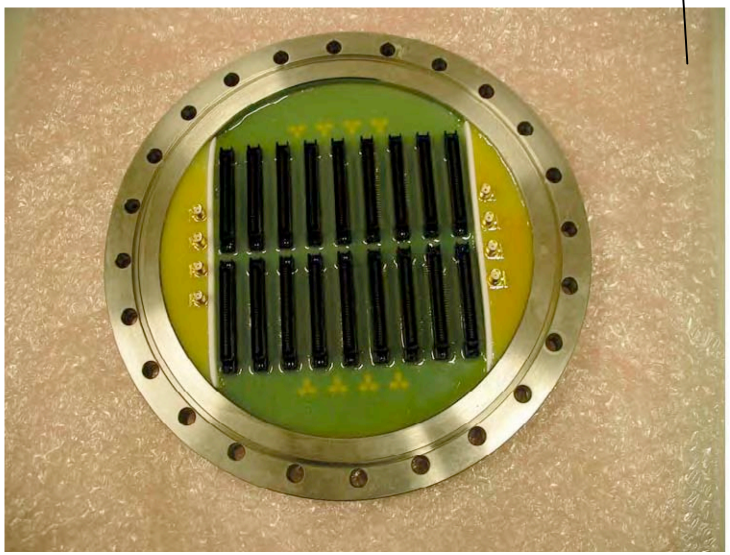
T600 cryostats layout



Electronics (54000 channels)

ICARUS front-end Electronics





100 UHV feed-throughs: 576 channels
(18 connectors x 32 + HV wire biasing)

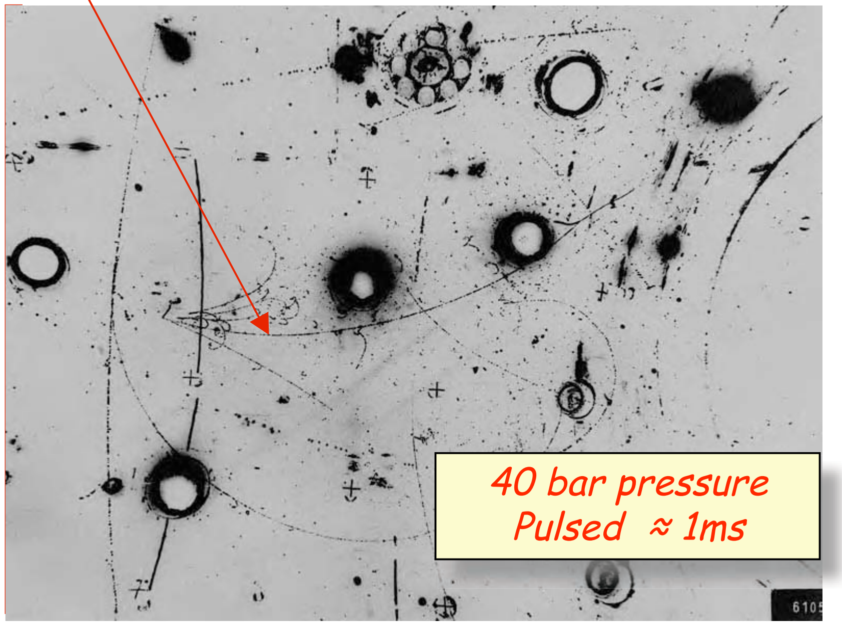
New Design based on multi-layer PCB with blind holes:
- electrical continuity
- ultra high vacuum tightness

Thirty years of progress........

LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

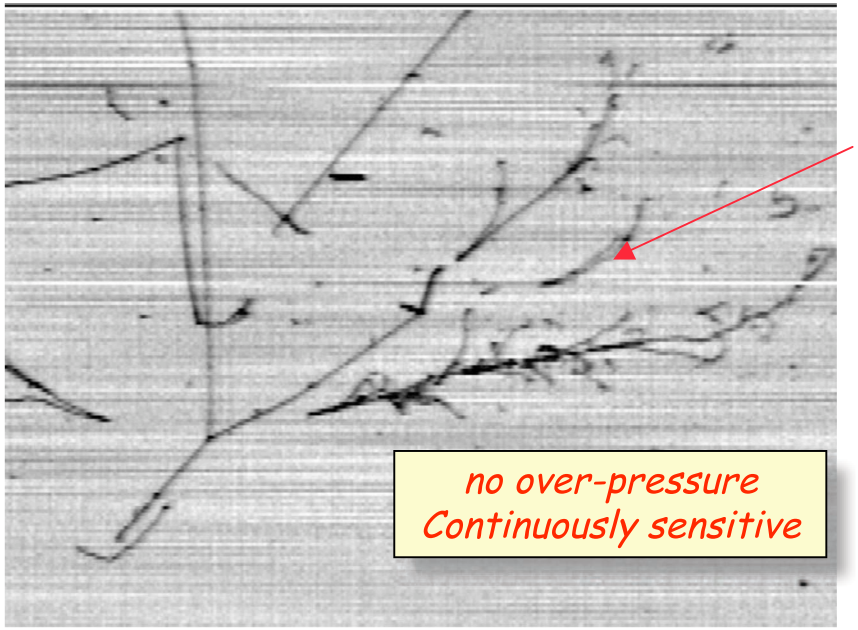
Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber



40 bar pressure
Pulsed ≈ 1ms

ICARUS electronic chamber

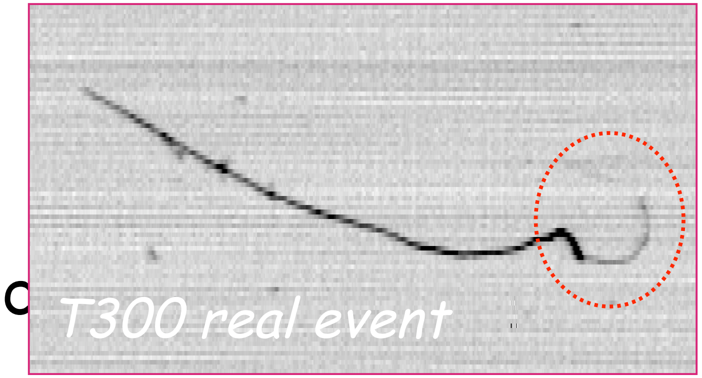


"Bubble" size $3 \times 3 \times 0.3\ mm^3$

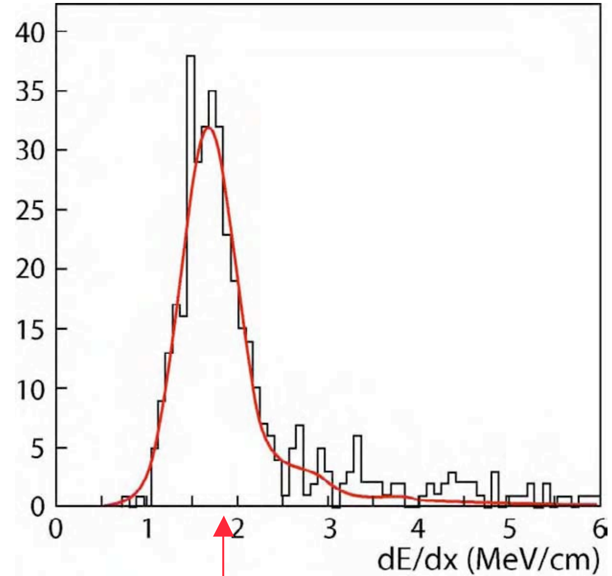
no over-pressure
Continuously sensitive

Medium	*Heavy freon*		Medium	*Liquid Argon*	
Sensitive mass	3.0	ton	Sensitive mass	Many ktons	
Density	1.5	g/cm^3	Density	1.4	g/cm^3
Radiation length	11.0	cm	Radiation length	14.0	cm
Collision length	49.5	cm	Collision length	54.8	cm
dE/dx	2.3	MeV/cm	dE/dx	2.1	MeV/cm

Summary of LAr TPC performances



- Tracking device
  - Precise event topology
  - Momentum via multiple scattering
- Measurement of local energy deposition dE/dx
  - e / γ separation (2%X_0 sampling)
  - Particle ID by means of dE/dx vs range
- Total energy reconstruction of the events from charge integration
  - Full sampling, homogeneous calorimeter with excellent accuracy for contained events



dE/dx distribution along a single muon track

RESOLUTIONS

Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

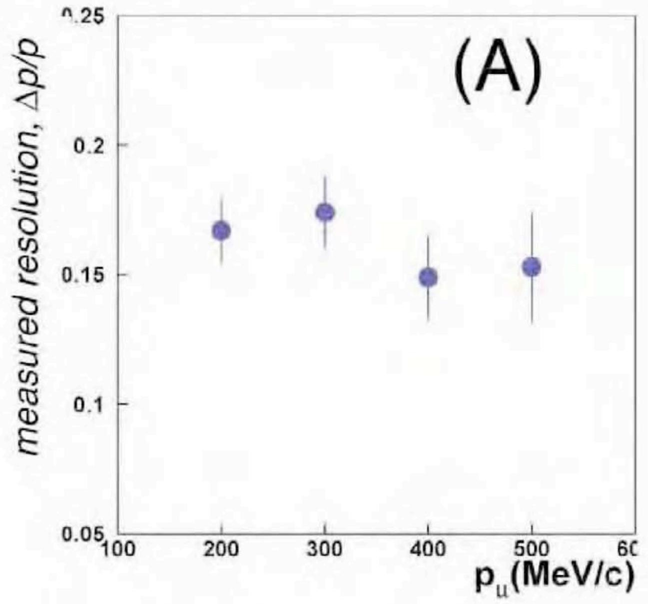
Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

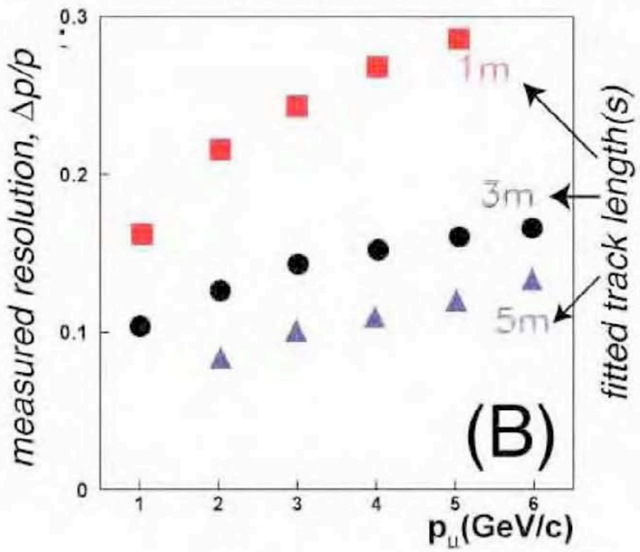
Muon momentum resolution by multiple scattering

- Muon momentum resolution $\Delta p/p$=15% (A) from multiple scattering [Kalman filter] has been measured for E < 0.5 GeV.
- The procedure, validated on stopping muons, has been extended to higher energy with MC calculations; the resolution $\Delta p/p$ can be as good as 10%, depending mainly on track length (B)

stopping muons

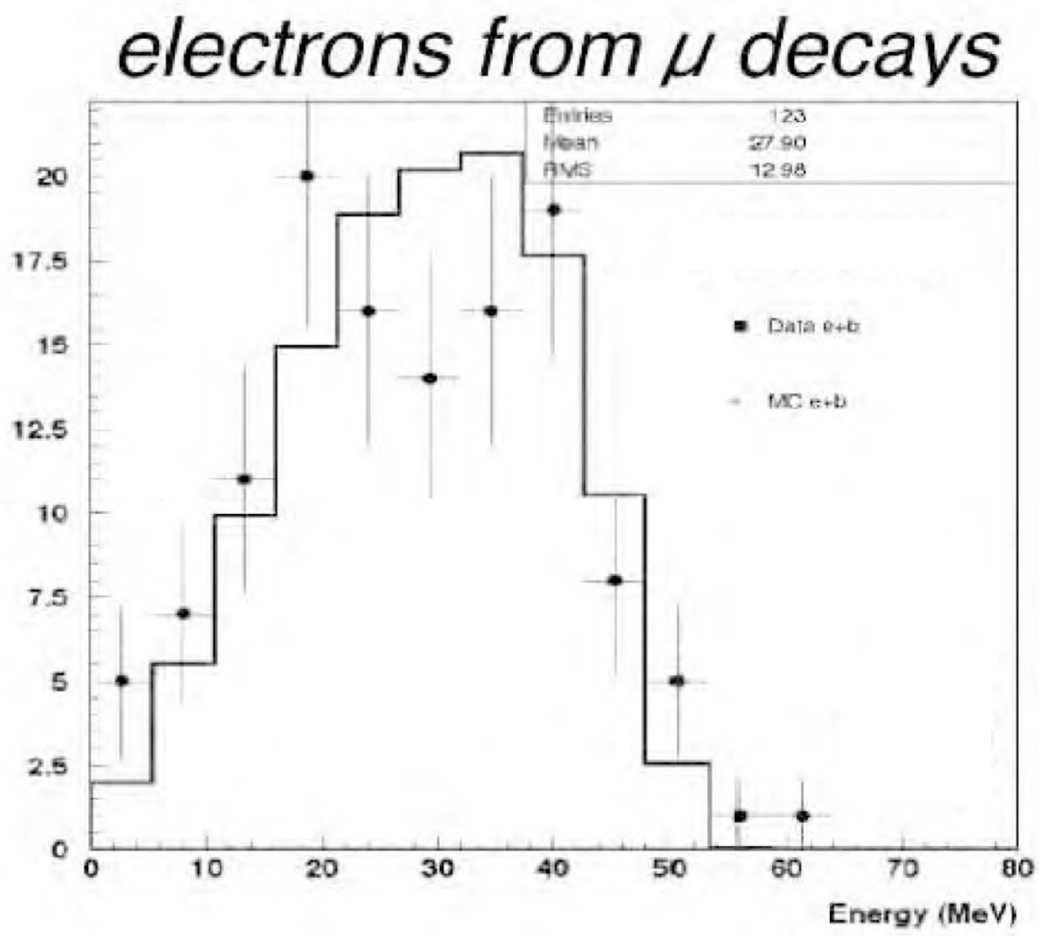


traversing muons
Kalman filter on segmented track



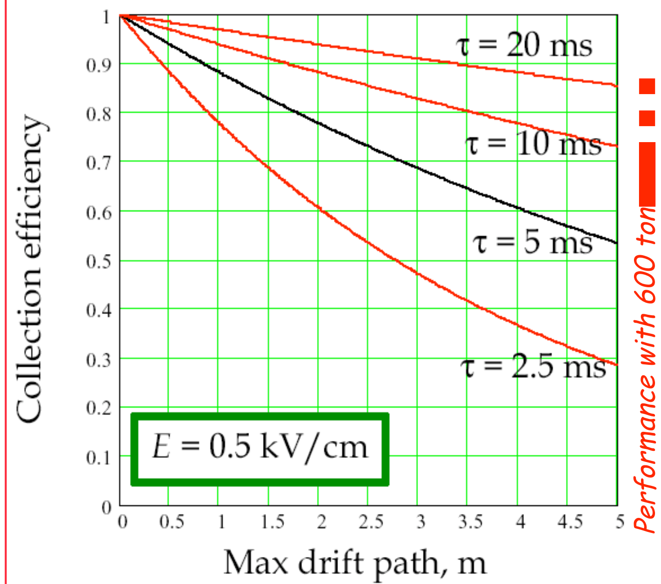
Electrons from muon decay

- Excellent resolution obtained from the measured decay electron spectrum (Michel parameter) from muon decays

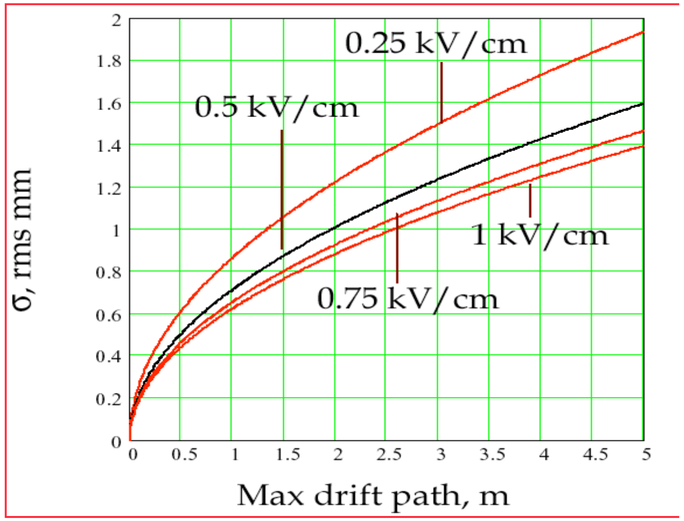


The key feature of LAr imaging: very long e-mobility

- The main technological challenge of the development of the cryogenic liquid Ar chamber is the capability of ensuring a sufficiently long free electron lifetime.
- Indeed the free electron path in a liquid is ≈ 600 times shorter than in a gas. For instance 10 ms lifetime corresponds to a 30 ppt (t=trillion !) of Oxygen equivalent.
- At 500v/cm, a 5m drift length corresponds to a drift time of 3.1 ms (1.6 m/ms).
- The intrinsic bubble size (rms diffusion) is given by $\sigma_D[mm] = 0.9\sqrt{T_D[ms]}$
- The values for 5m drift are $\langle\sigma_D\rangle \approx$ 1.1 mm and $\sigma_{max} \approx$ 1.6 mm , tiny with respect to the wire pitch (≥ 2mm).

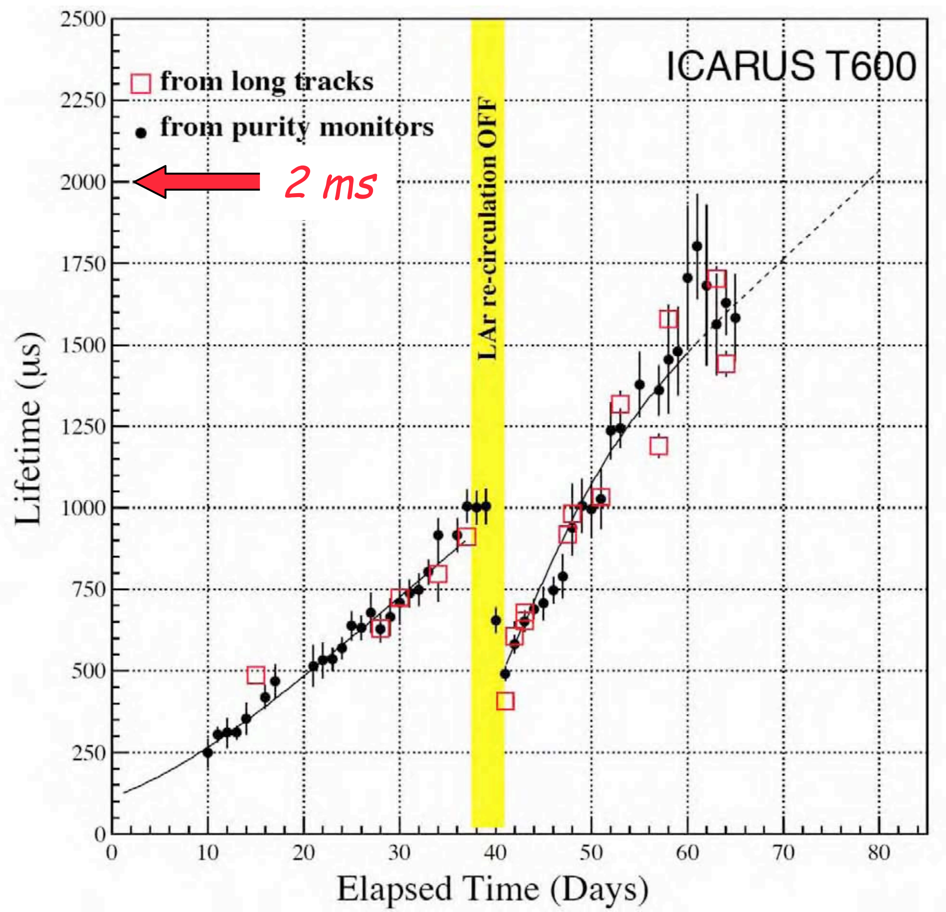


Drifting charge attenuation versus drift path at different electron lifetimes



“Purity”: status of the art in 2001

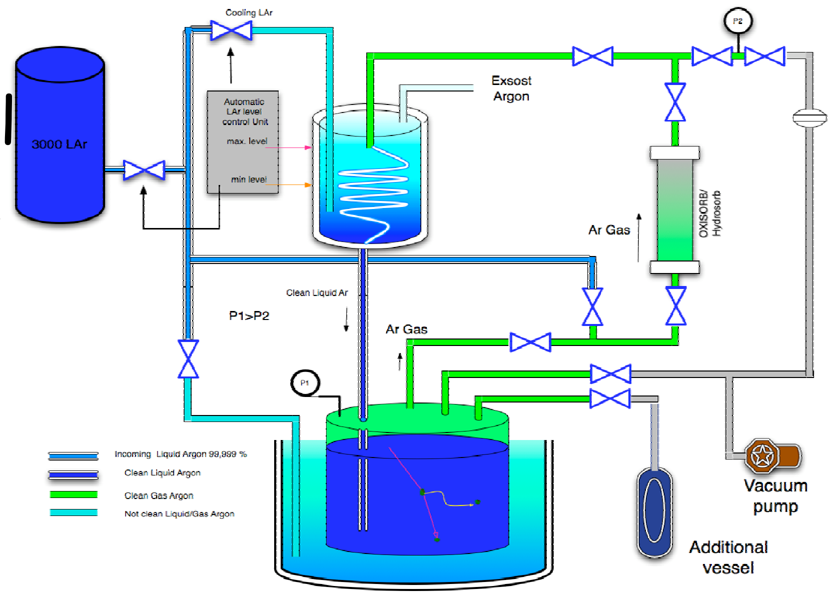
- During 2001 a first real size test of the 1/2 of the T600 detector was performed on surface in Pavia.
- In the detector the drift length was set to 1.5 m, corresponding to a drift time of about 1 ms.
- The purity performance at that time is shown here, measured both with purity monitors and muon tracks.

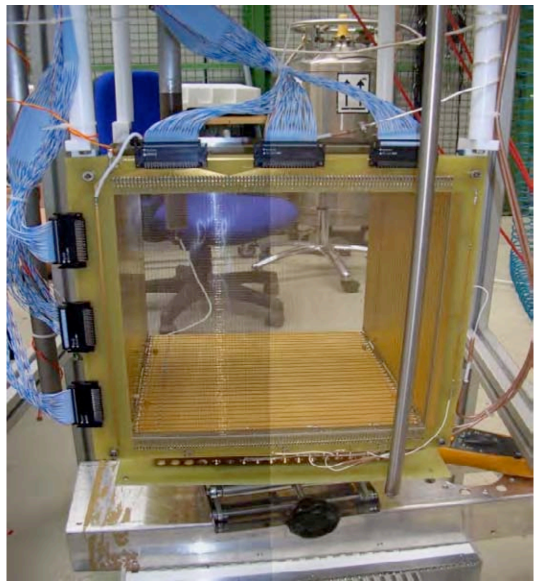


- A considerable progress over the last few years has permitted to reach industrial purification techniques which are capable of a much better performance.

Recent progress in experimental purity achievements

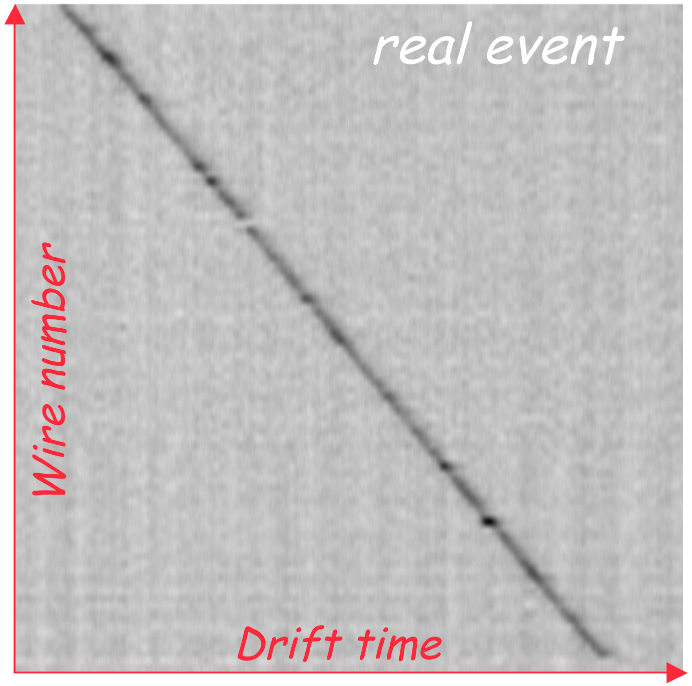
- New industrial purification methods have been developed at an exceptional level, especially remnants of O_2 which have to be initially and continuously purified.
- Extremely high τ_{ele} have been determined with cosmic μ's in a small 50 litres LAr-TPC.
- The short path length used (30 cm) is compensated by the high accuracy in the observation of the specific ionization
- The result here reported is τ_{ele} ≈21 ms corresponding to ≈15 ppt, namely a ≈10^{-11} molecular impurities in Ar

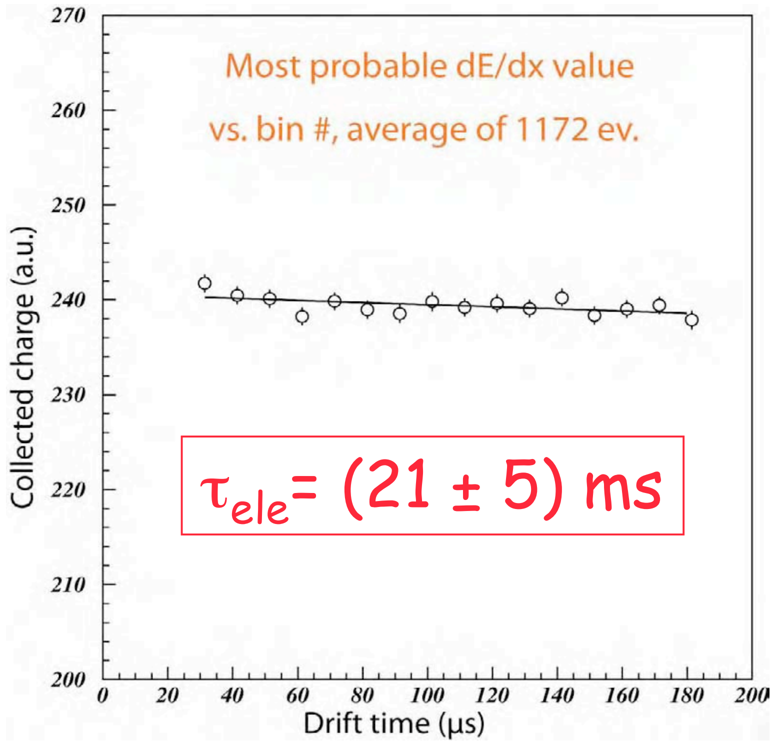


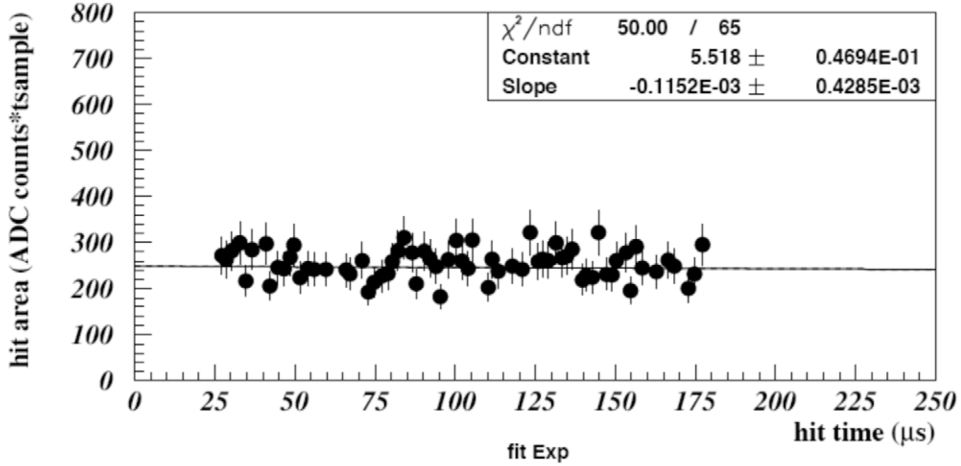


ICARINO-Legnaro

- The measured value to the experimental τ_{ele} corresponds to an attenuation of about 10 % for a longest drift of 5 meters, opening the way to exceptionally long drift distances.







Free electron lifetime: experimental determination in T600

- Electron Lifetime is measured in the underground T600 detector by the charge signal attenuation versus drift time in Collection view for through-going straight muon tracks (1 /(hour m^2).
- Request for a track to be "good for purity":
  - At least 50 wires and 1200 t-sample both in Collection and Induction2 views
  - Reduced e.m. activity along the track: no delta-rays near the track
- A simple model: uniform distribution of the impurities, internal degassing, decreasing in time because of an external leak balanced by liquid recirculation (t_{ele} [ms] = 0.3 / N[ppb])

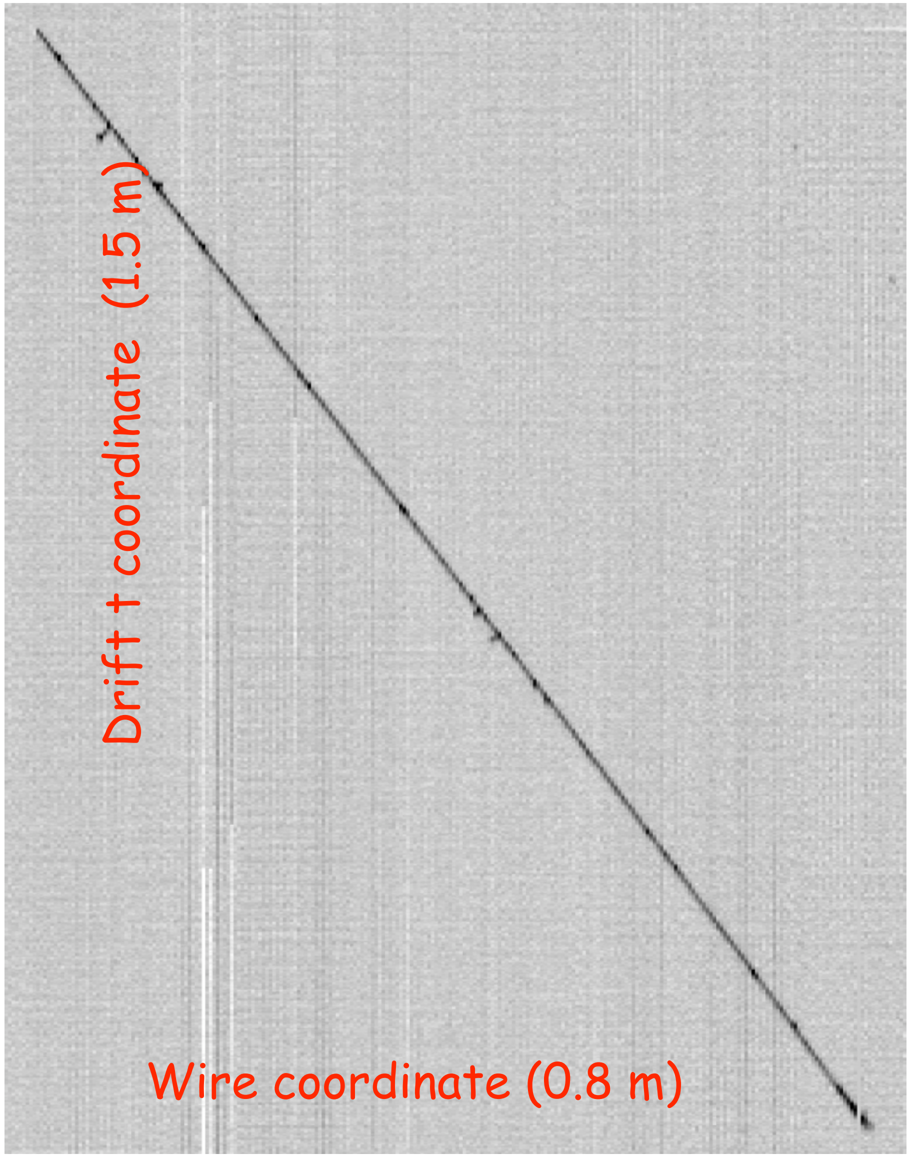
$$\boxed{dN/dt = -N/\tau_R + k + k_I \exp(-t/\tau_I)}$$

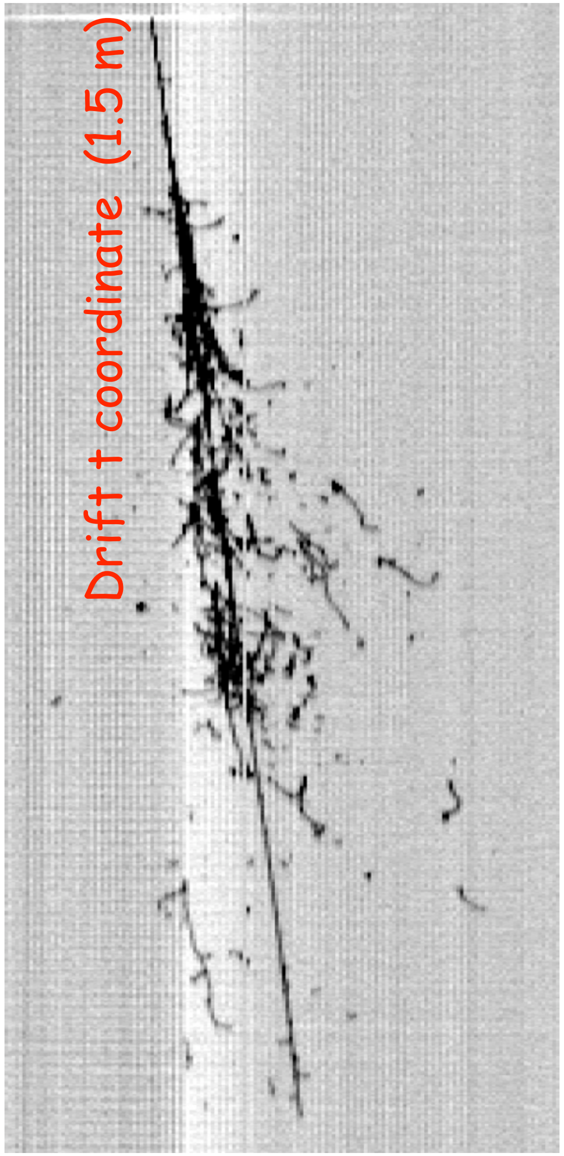
τ_R: recirculation time of the full detector volume

k_I and τ_I : related to the total degassing internal rate

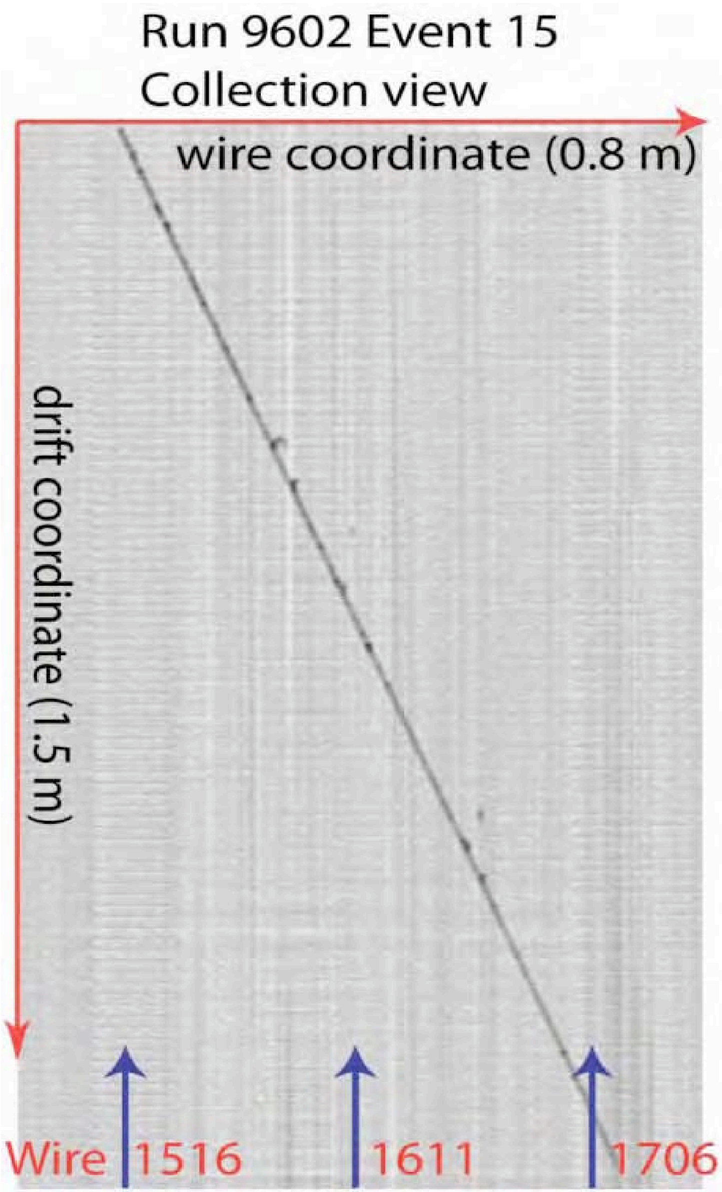
k : related to the external leaks

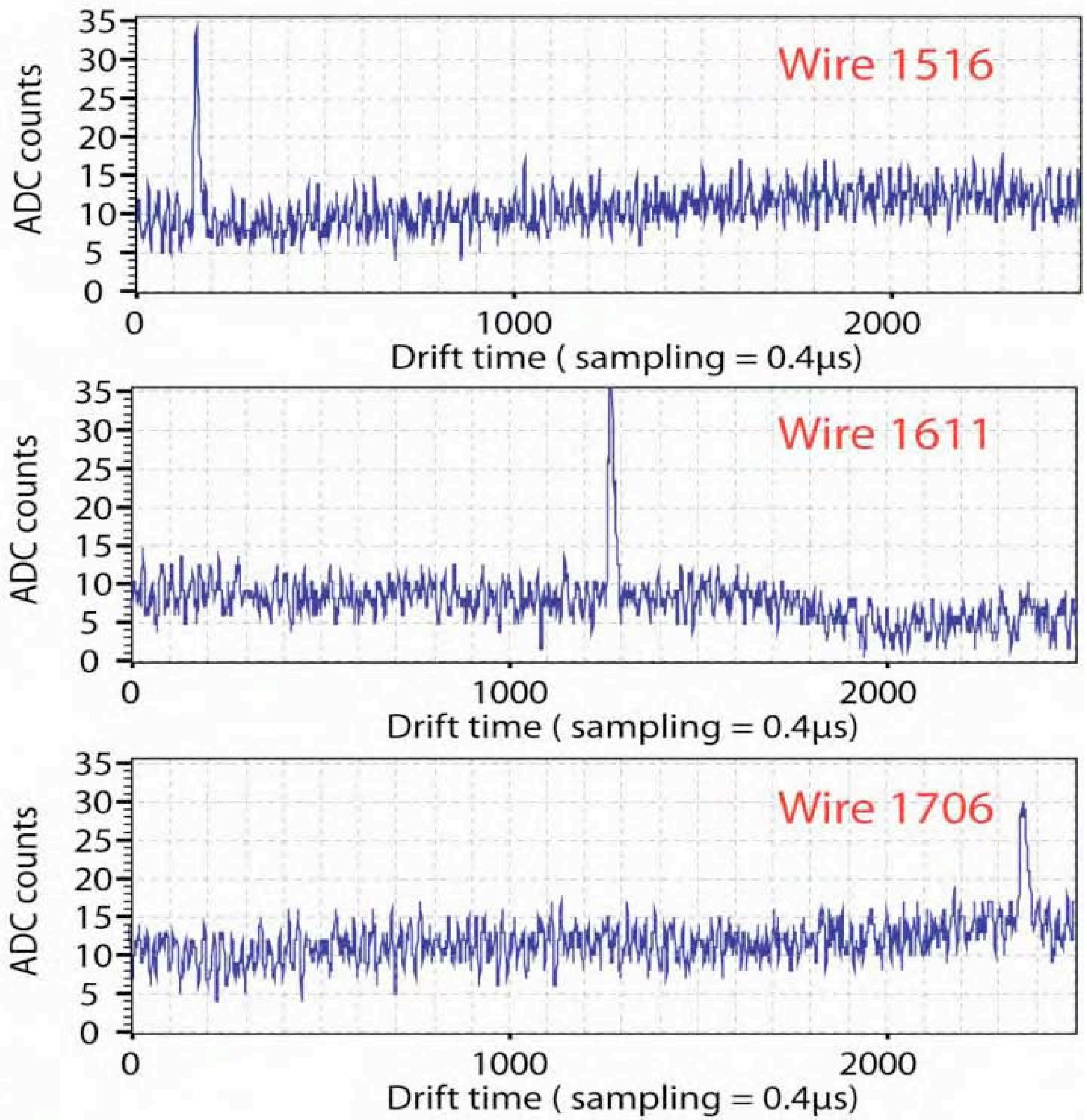
Cosmic μ interaction underground in ICARUS T600



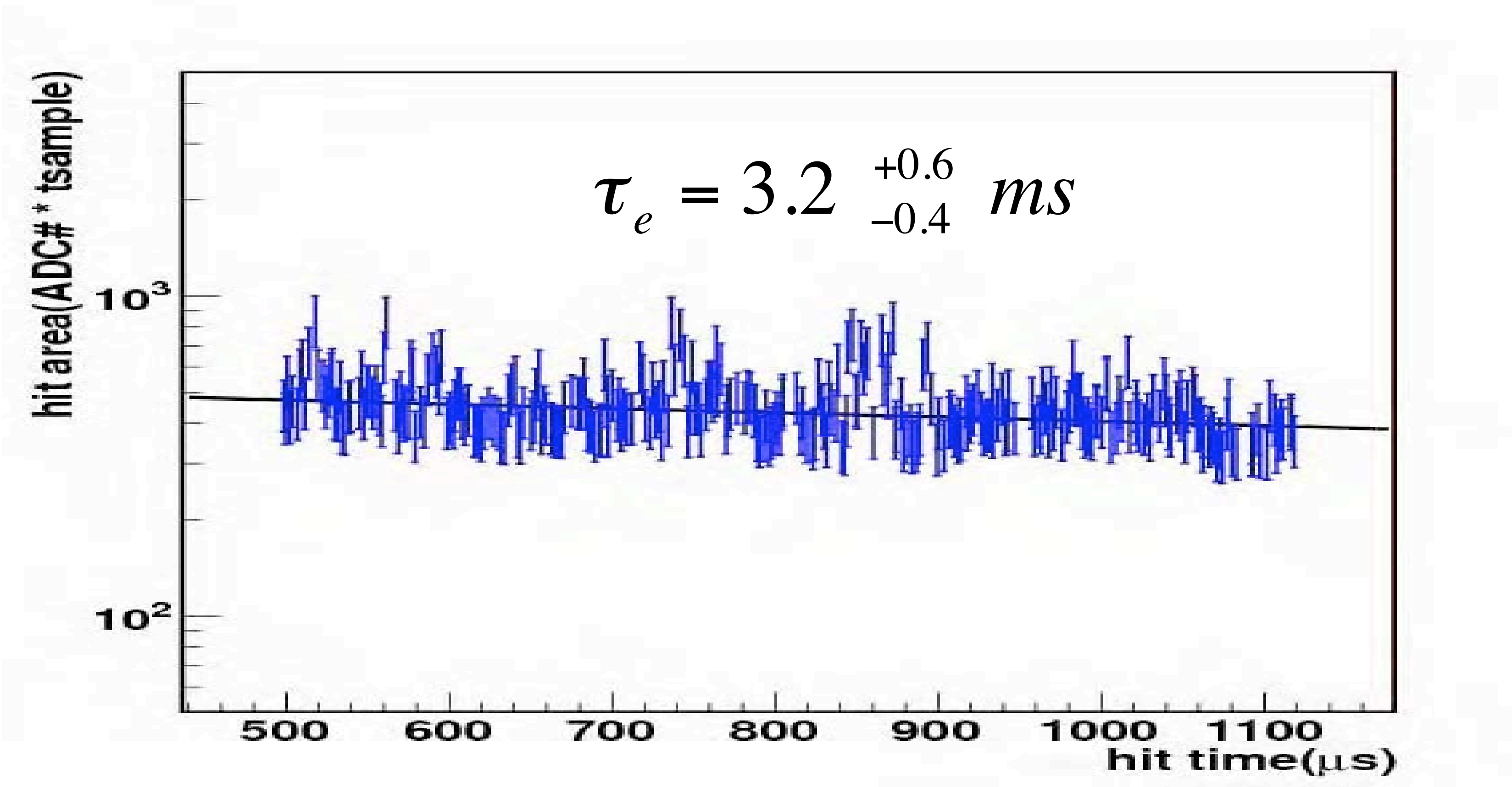


A “track good for purity” in the T600

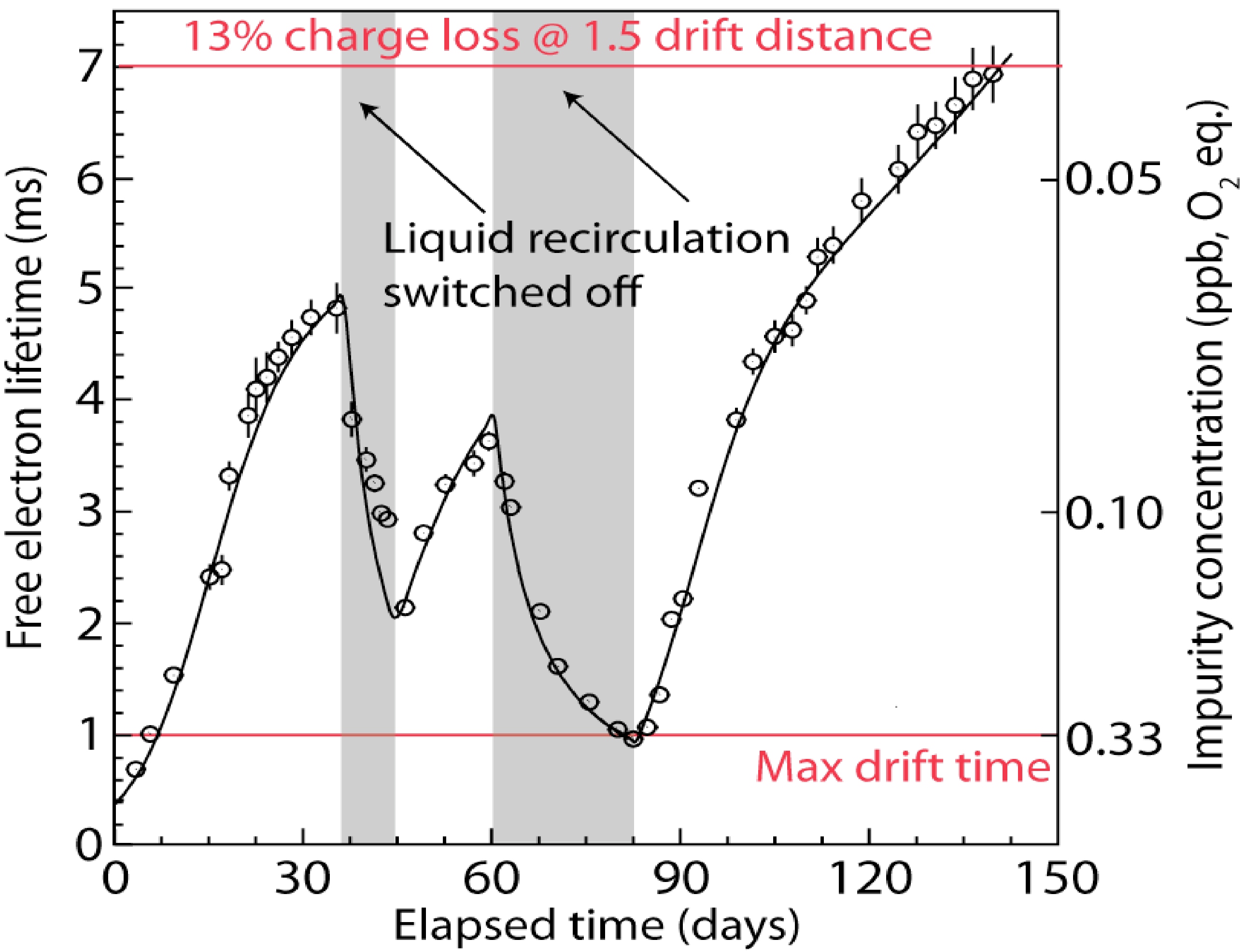




Single track analysis: an example



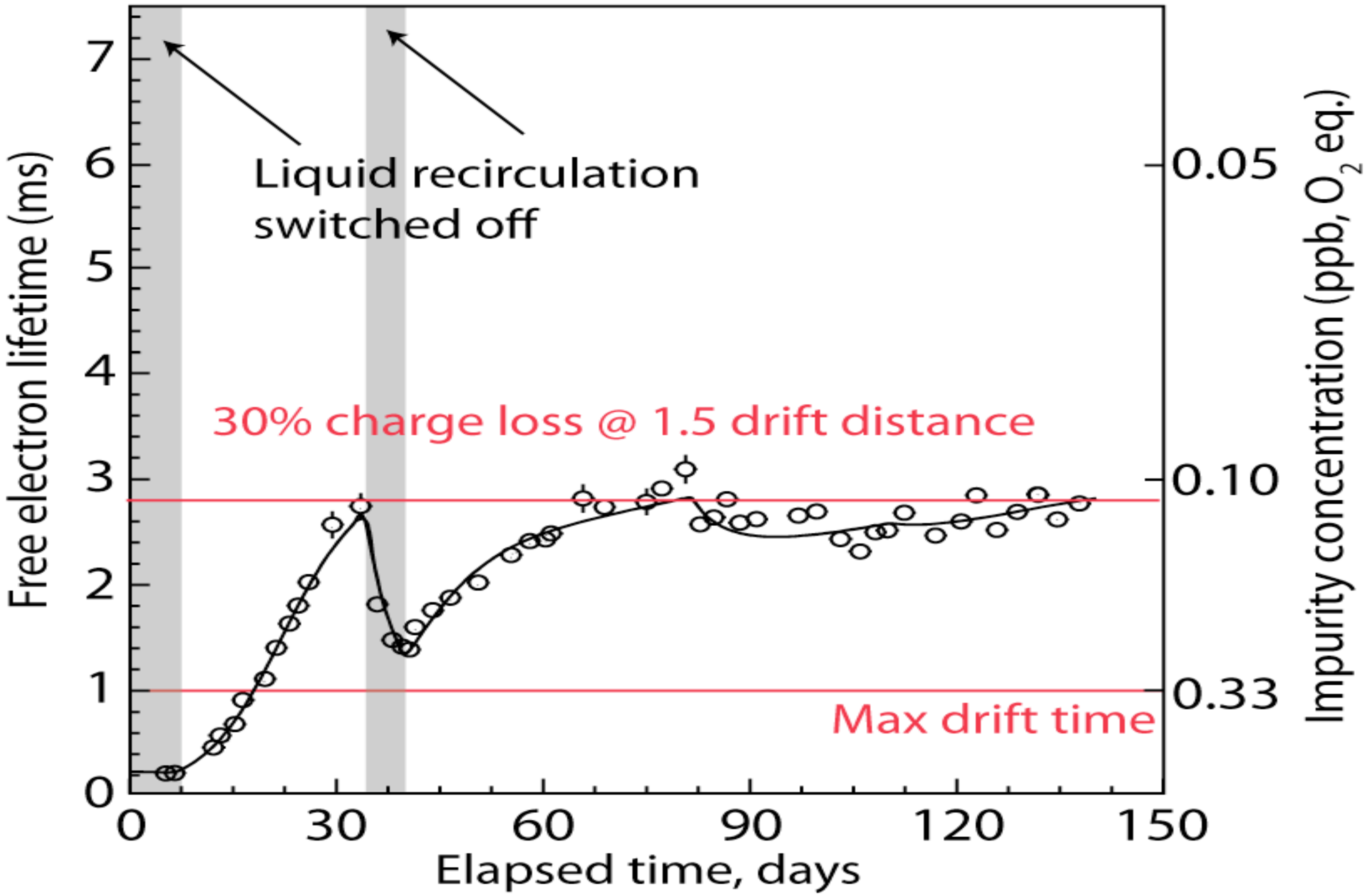
Purity Measurement results:West Module



The electron lifetime is still increasing:

- Internal degassing and external leak very small

Purity Measurement results: East Module



The electron lifetime is ~ 2.7 ms in the last 2 months:

- The comparison with the West module: reduced internal degassing
- Possible external impurity contribution under investigation

Purity Measurement: simple fit to data

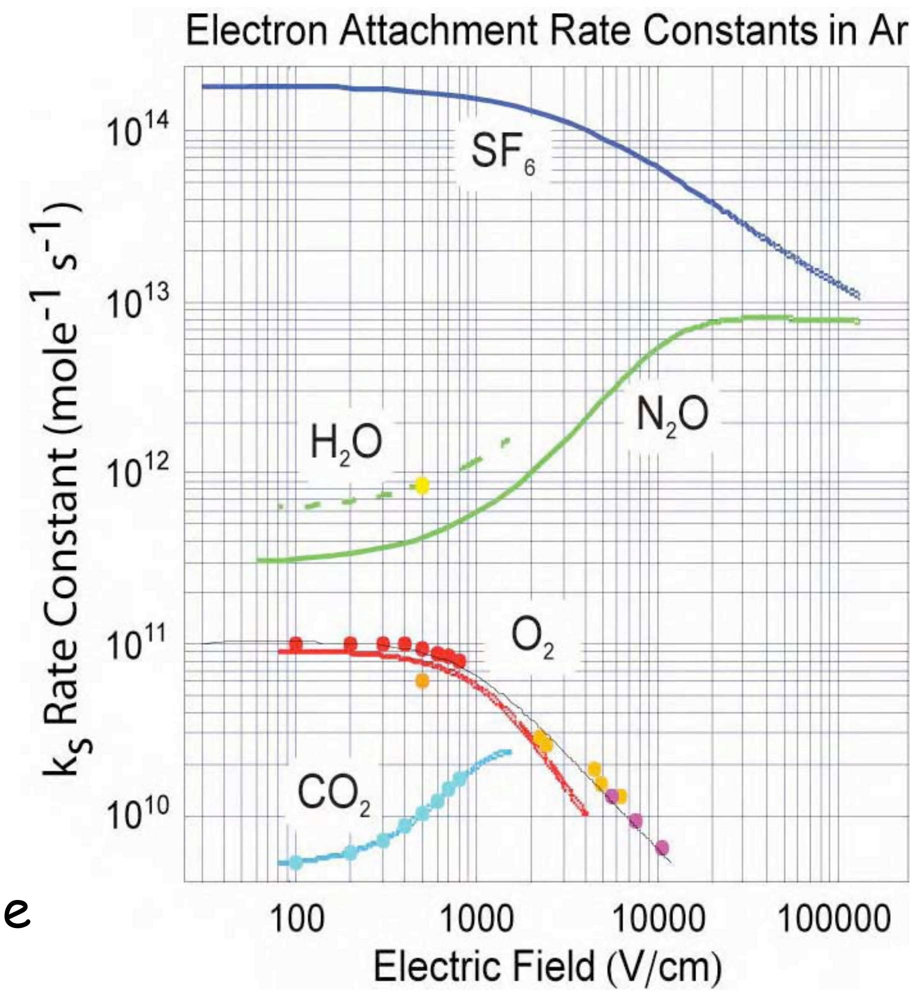
Unaccounted difference in the degassing times !

	West	East
Initial impurity [ppb]	0.771 ± 0.013	1.787 ± 0.035
External leak rate [ppt/day]	0. ± 0.33	2.1 ± 0.44
Initial internal degassing [ppt/day]	0.50 ± 0.015	0.80 ± 0.019
Degassing reduction time [days]	103.5 ± 2.25	213.4 ± 26.0
Recirculation time 1 [days]	5.86 ± 0.04	5.37 ± 0.05
Recirculation time 2 [days]	6.36 ± 0.06	5.92 ± 0.09
Recirculation time 3 [days]	5.85 ± 0.04	6.10 ± 0.03
Recirculation time 4 [days]	-	5.67 ± 0.09

Nominal recirculation time of purifier: 2 m^3/h x 2 corresponding to ≈ 6 day cycle time

Reduced lifetime of the East module ?

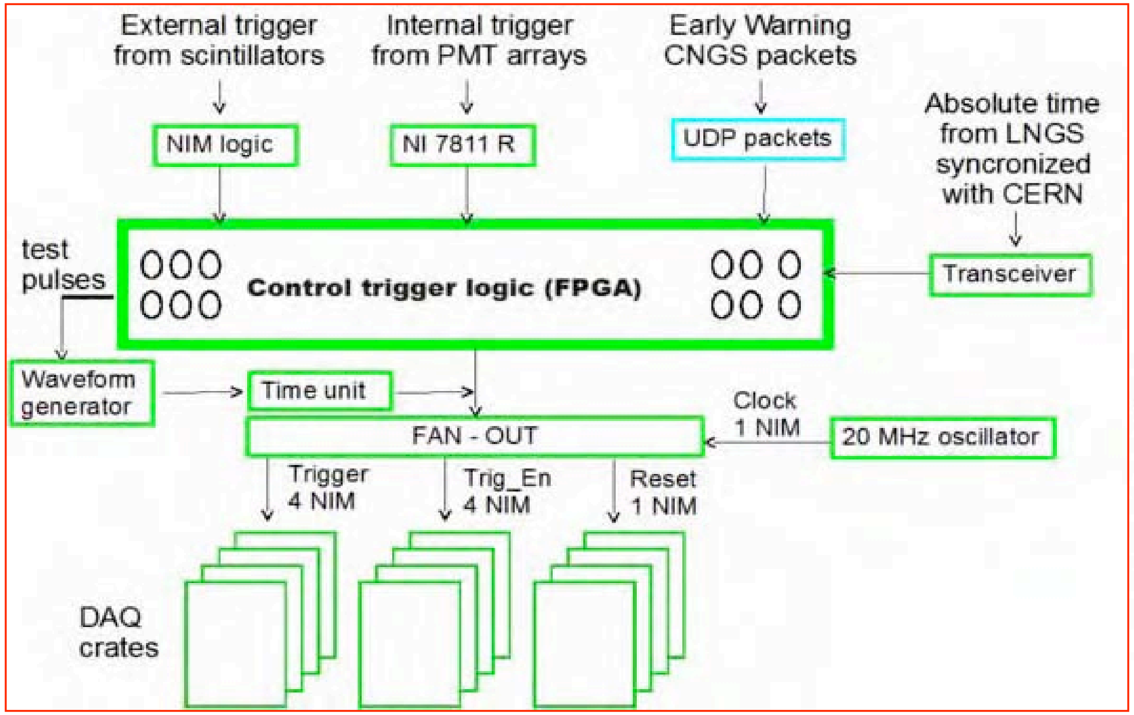
- The East module has undergone some unwanted, accidental events:
  - Initial purity much lower before recirculation
  - Recovery from HV feedthrough failure
  - Accidental overpressure with loss of about 2 m^2 of LAr to air
- Both modules have similar purification rates (full recirculation in 6 days)
- The shorter lifetime (3ms) is remarkably constant over many weeks
- Many alternatives but the presence of some "relic" impurity not cleared by the purifier very likely (N_2, H_2O, CO_2, ?)
- Gas chromatograph measurements in progress



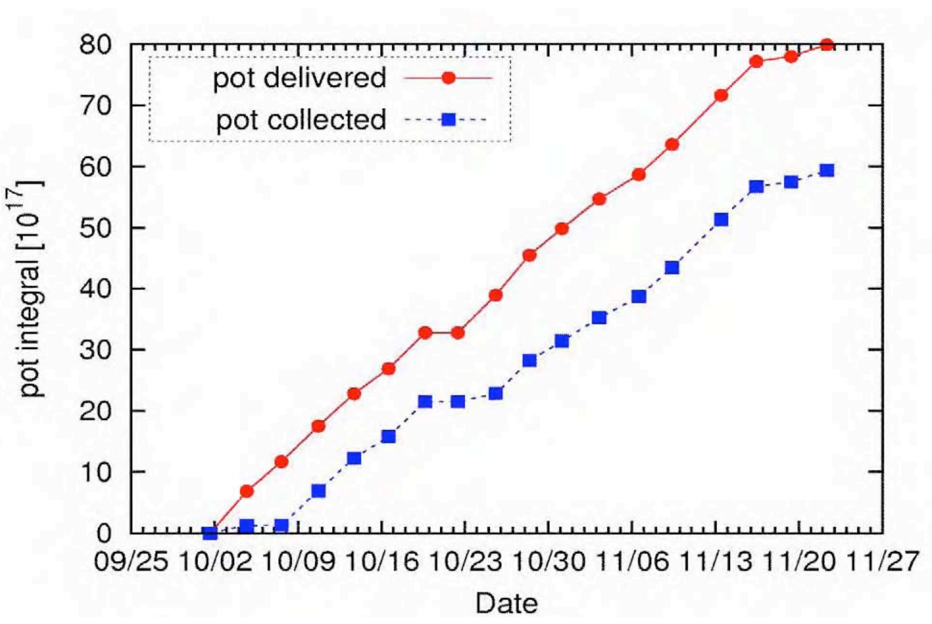
$k_s(N_2) \sim k_s(O_2)/760$
For 0.5<E<3.0 kV/cm

CNGS2 runs during 2010

- At every CNGS cycle 2 proton spills lasting 10.5 μs each, 50 ms apart.
- Trigger with the photomultiplier signal for each chamber: low threshold discrimination (~ 30 mV), coincident with a 60 μs long beam window.

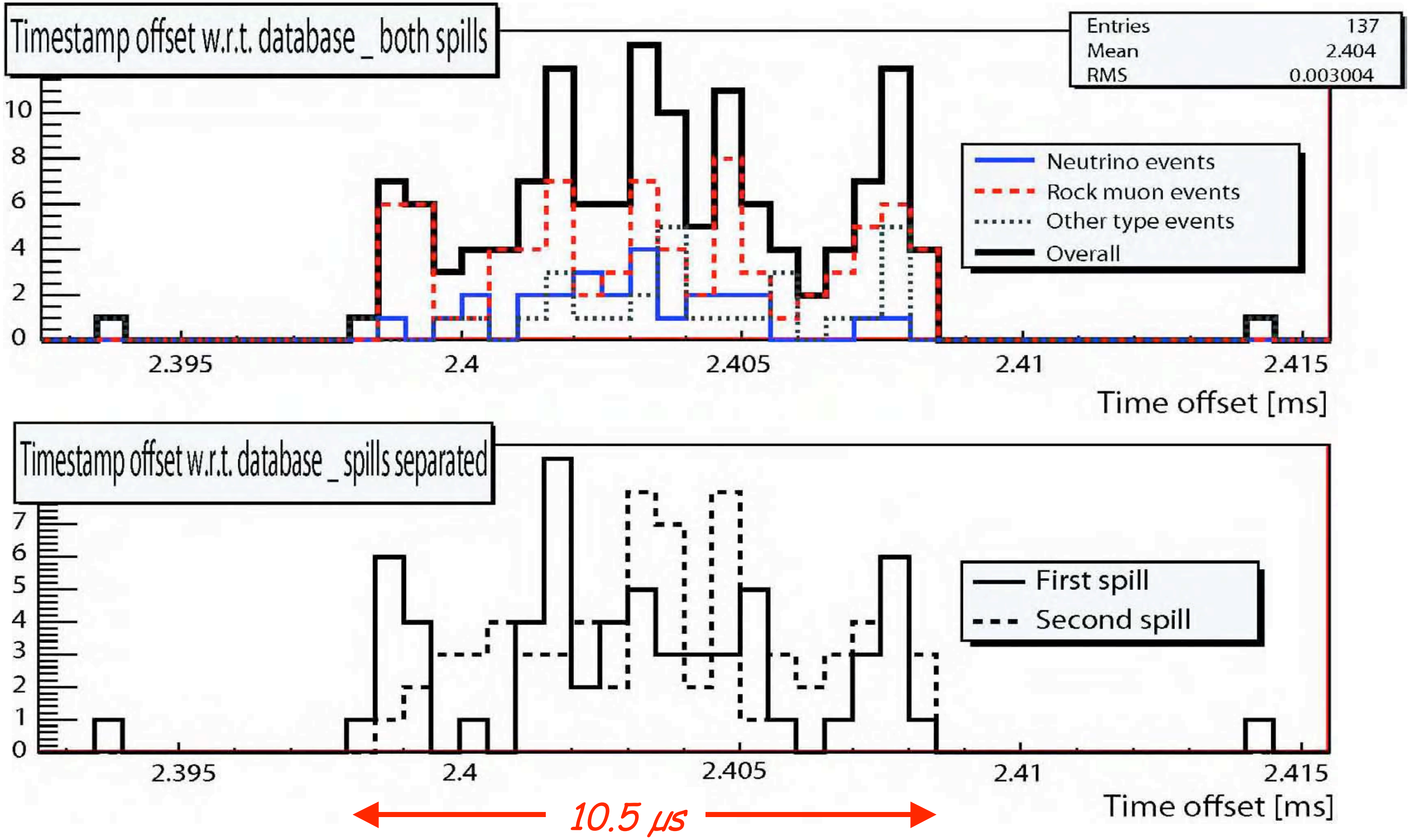


Oct. 1st ÷ Nov. 22nd: $8 \cdot 10^{18}$ pot delivered, $5.9 \cdot 10^{18}$ pot collected with detector lifetime up to 90% since Nov. 1st.



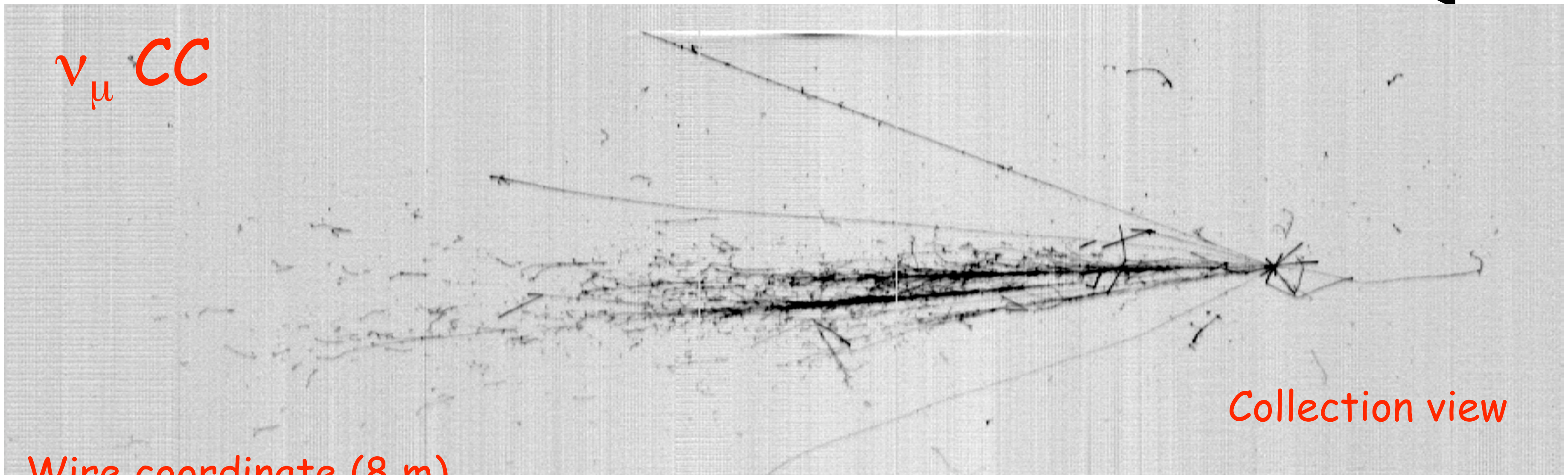
CNGS events timing w.r.t. CERN proton extraction time

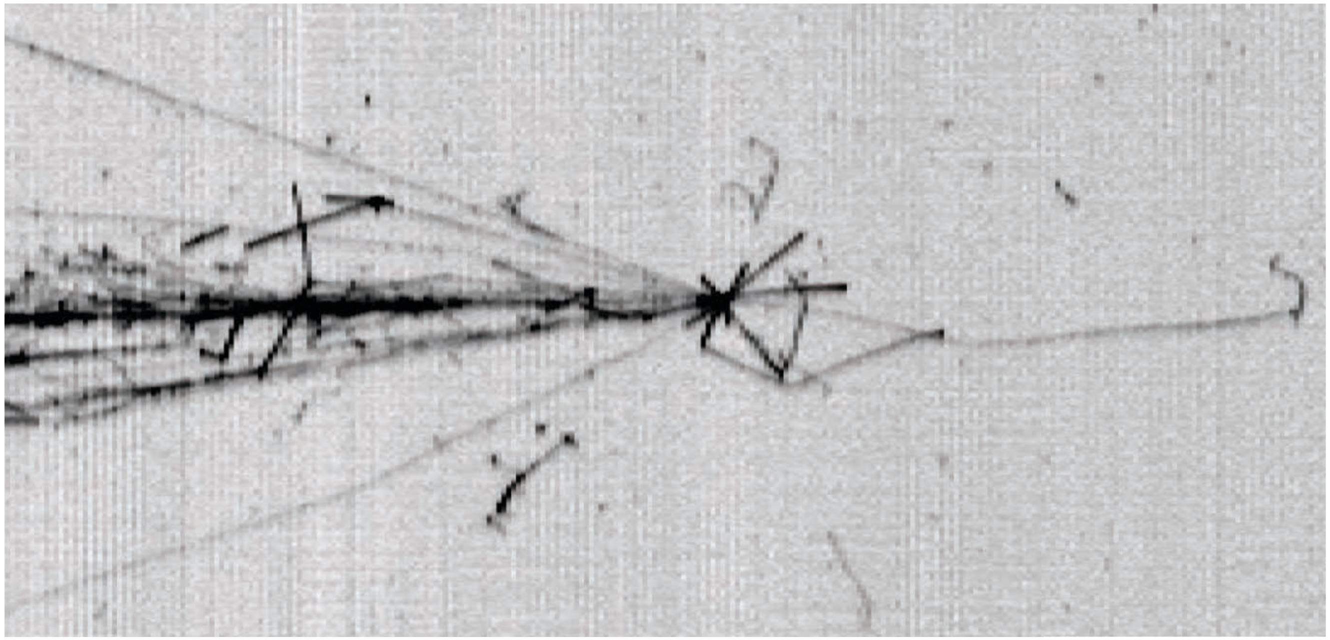
- Very narrow beam distribution: only 10 μs wide ≈ spill duration (10.5 μs)
- Mean offset value (2.404 ms) in agreement with ν t.o.f. (2.437 ms) in view of ~ 40 μs fiber transit time from ext. LNGS labs to Hall B (8km)



CNGS “first” neutrino interaction in ICARUS T600

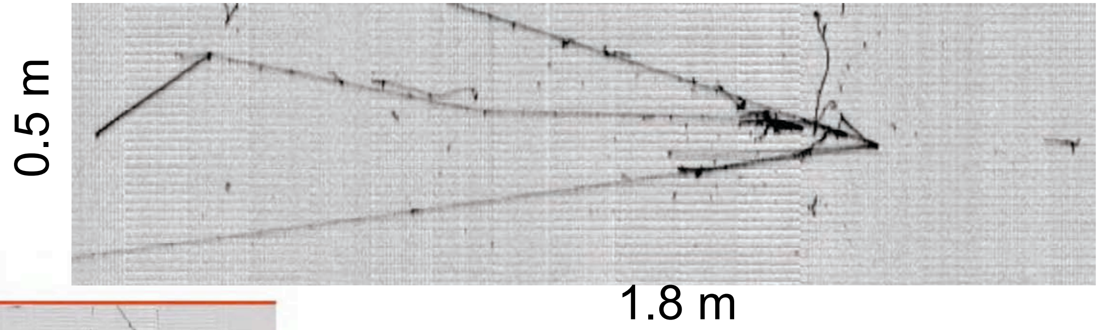
CNGS ν beam direction

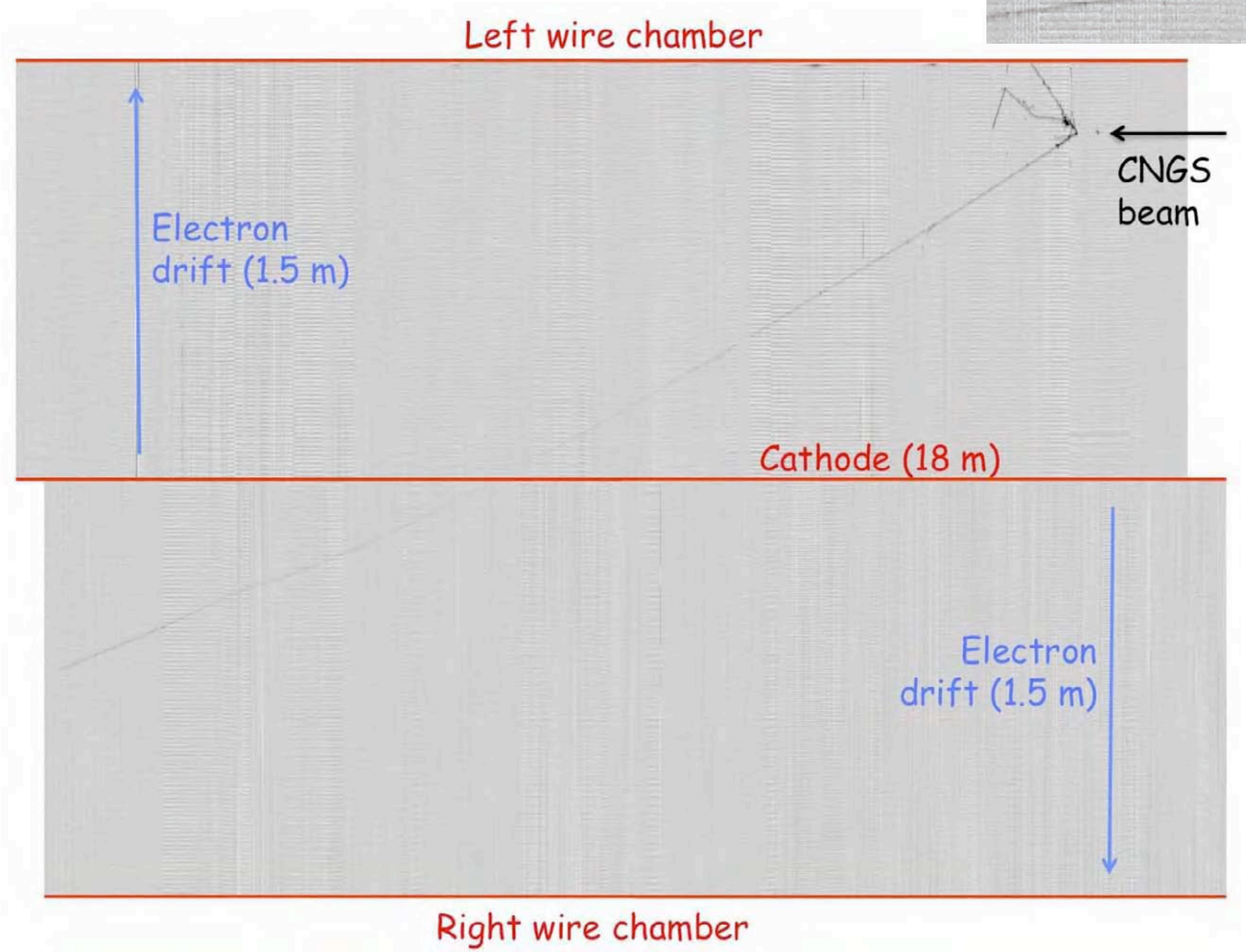




Selected events are reconstructed, analyzed and qualify reconstruction /analysis programmes

Low energy CNGS ν_μ CC interaction

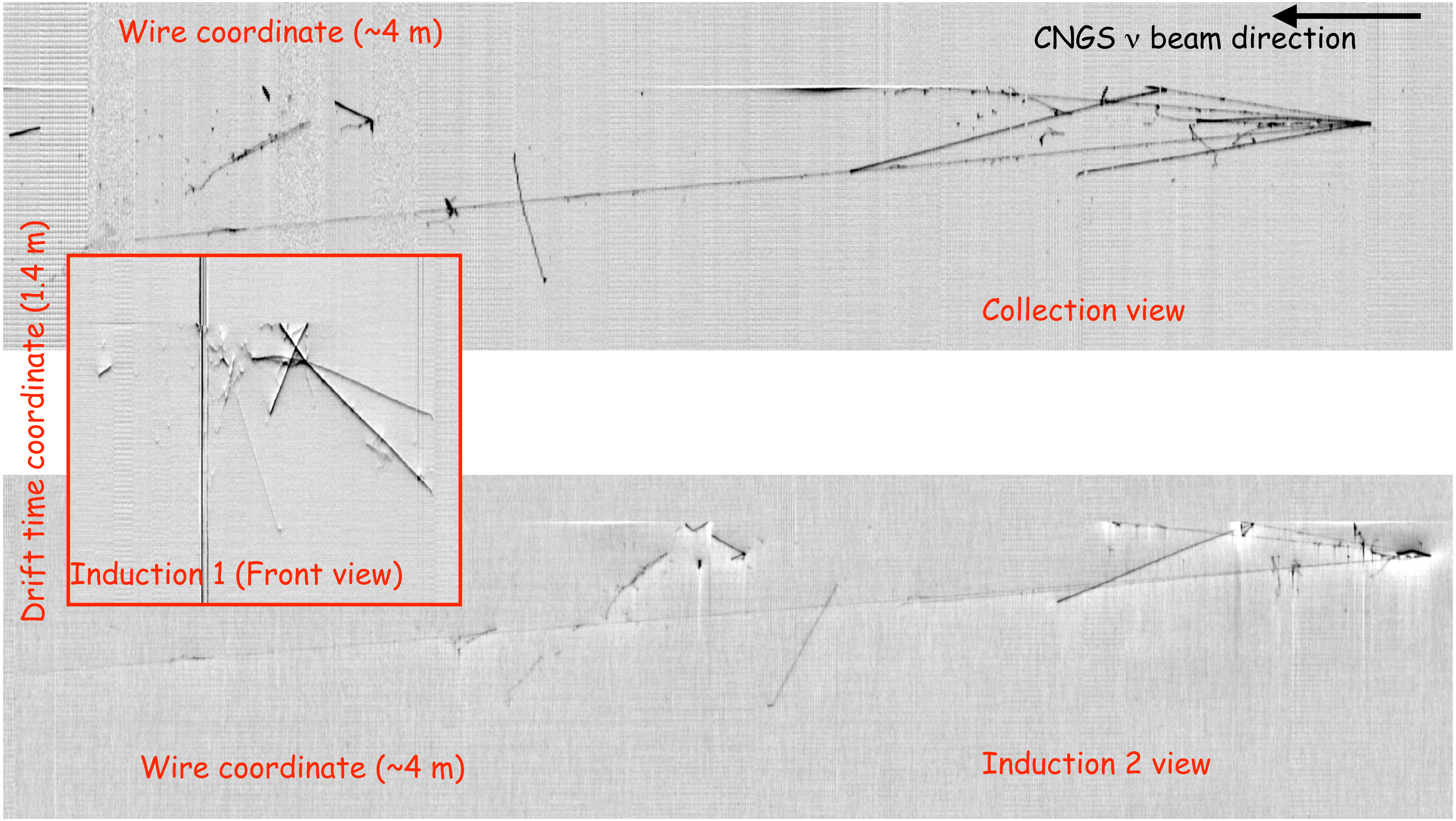




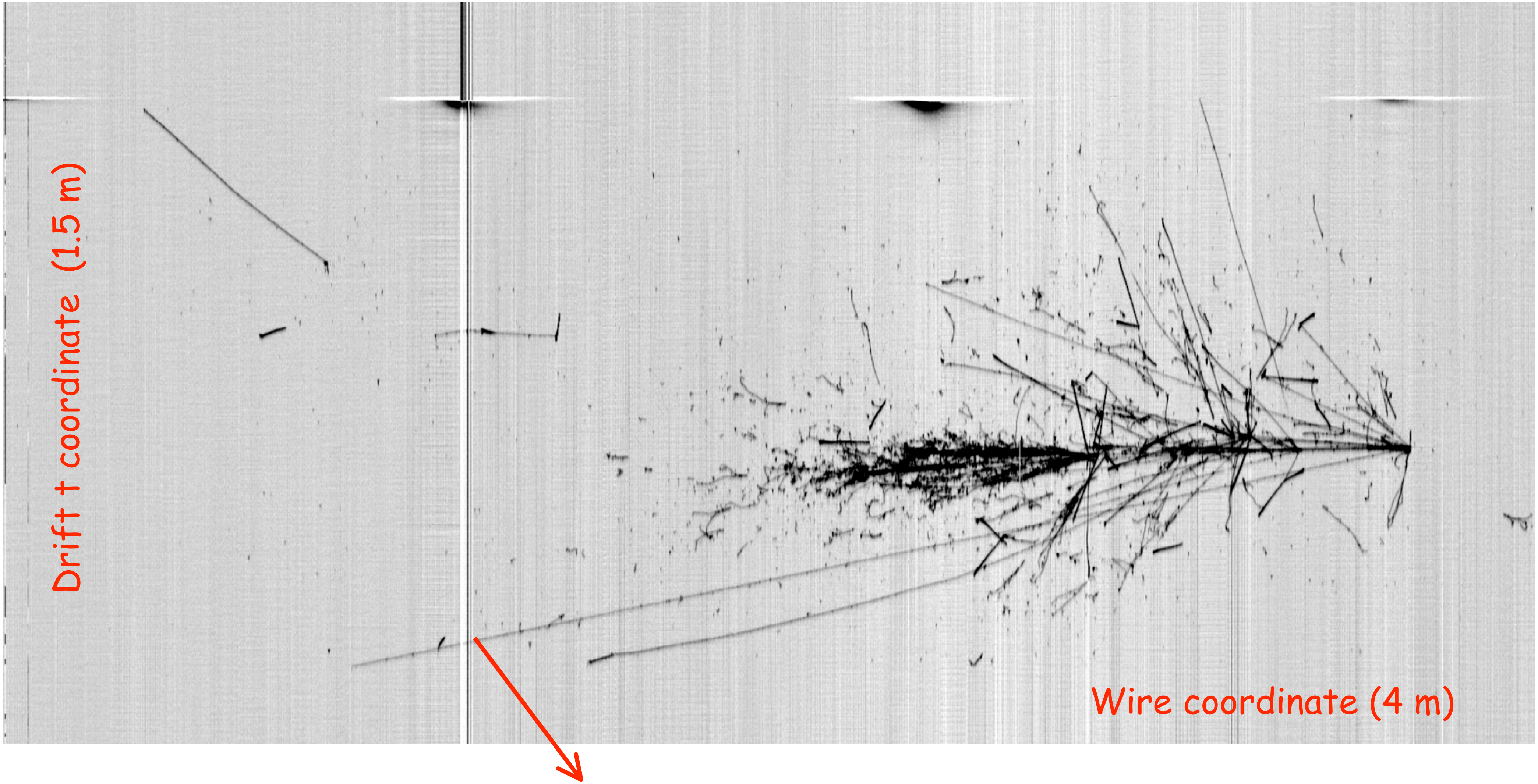
E_{vis} ~ 9 GeV
Electron lifetime and quenching accounted for

Collection views (not to scale!)

CNGS neutrino ν_μ CC interaction

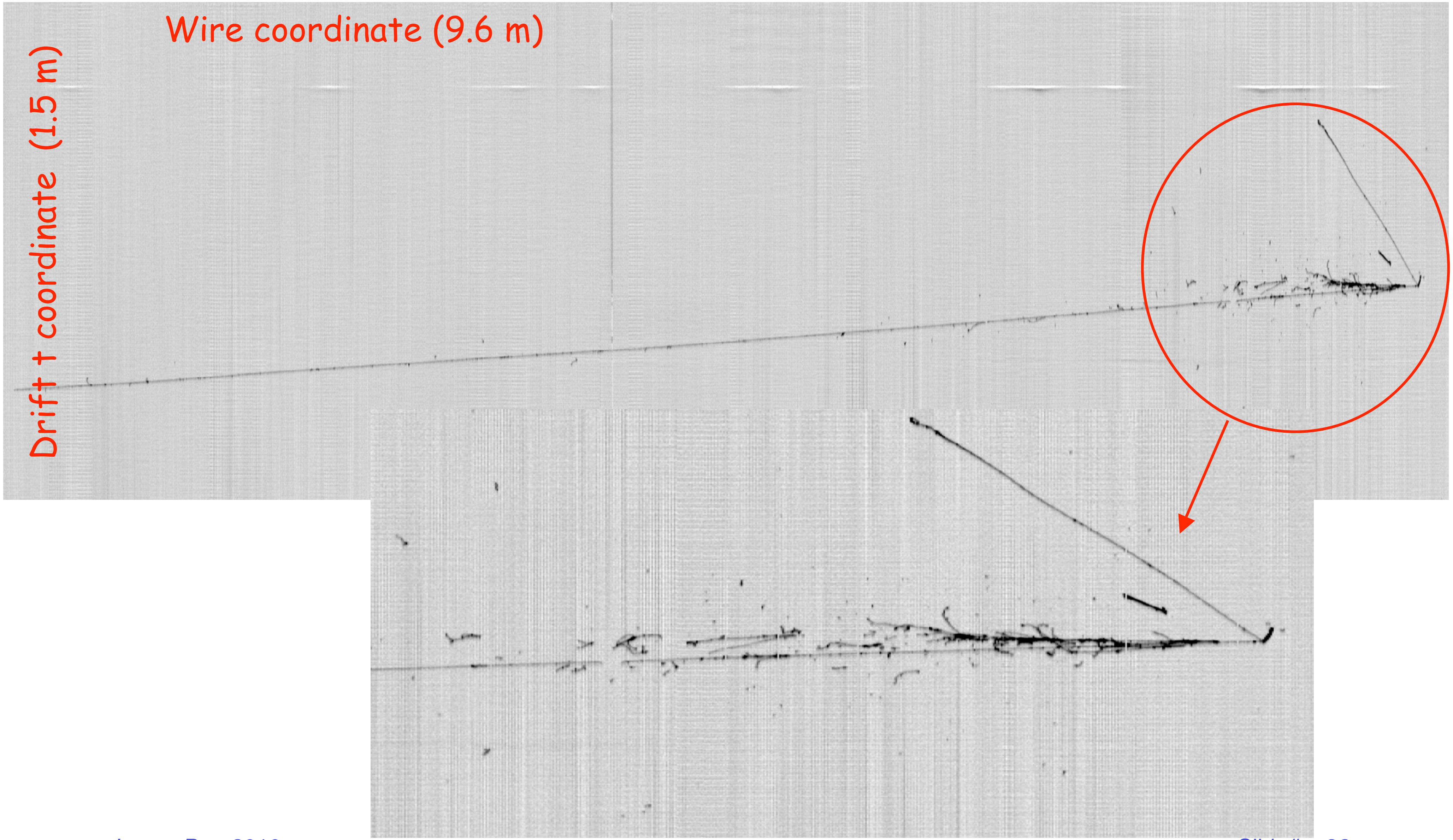


CNGS ν_μ CC interaction in ICARUS T600



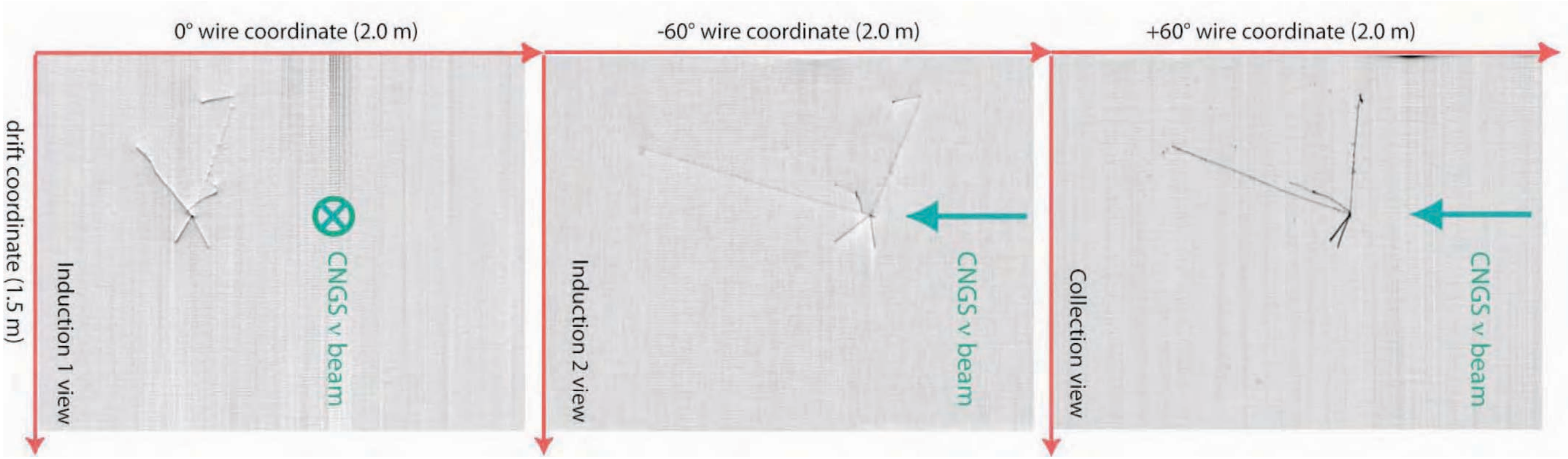
μ continuing in adjacent TPC chamber

CNGS ν_μ CC interaction in ICARUS T600



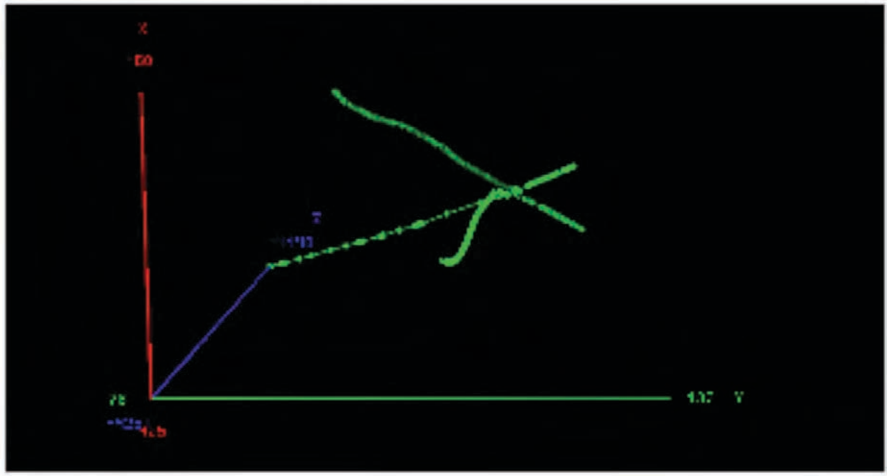
CNGS NC interaction in ICARUS T600

Very low energy CNGS neutrino interaction



Total visible energy: 770 MeV (including quenching and electron lifetime corrections)

Very small event

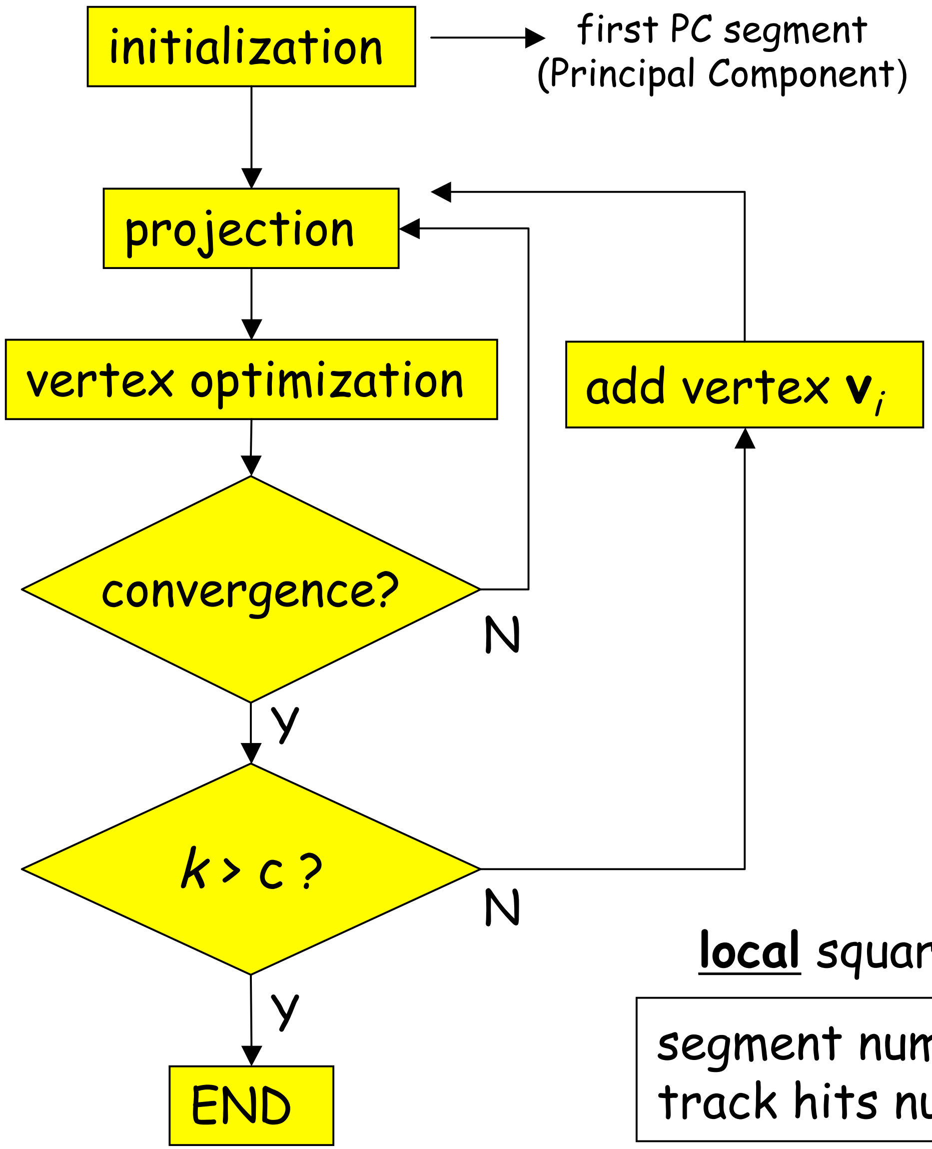


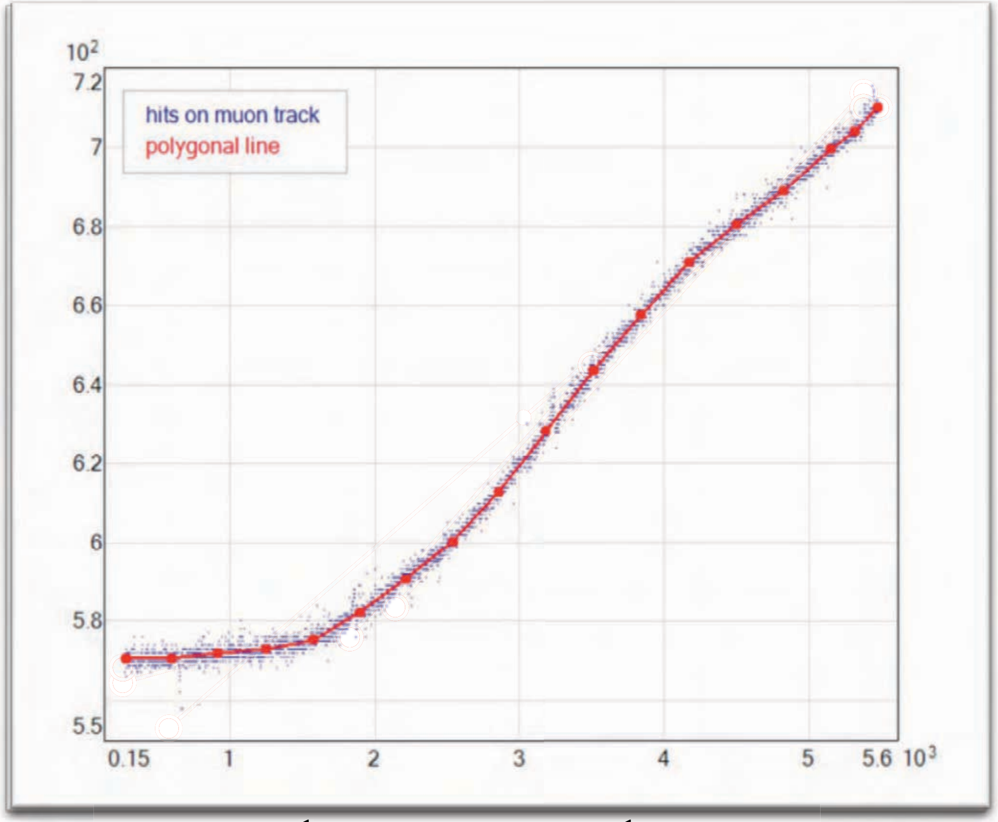
Outline of the 3D reconstruction

- Complement of 2D reconstruction
  - It is based on Polygonal Line Algorithm (PLA) [1]
  - The procedure of sorting hits along 2D tracks independly in each view:
- As a result of the PLA application
  - **PLA-FIT** through hits of a track
  - both hits and hit projections to the fit are sorted along the track
- 3D reconstruction: Linking hit projections_between views according to
  - drift sampling
  - sequence of hits

[1] http://www.iro.umontreal.ca/~kegl/research/pcurves/

Polygonal 3D Line Algorithm





$$G(\mathbf{v}_i) = \frac{1}{n}\Delta_n(\mathbf{v}_i) + \lambda \frac{1}{k+1} P(\mathbf{v}_i)$$

local squared distance to hits

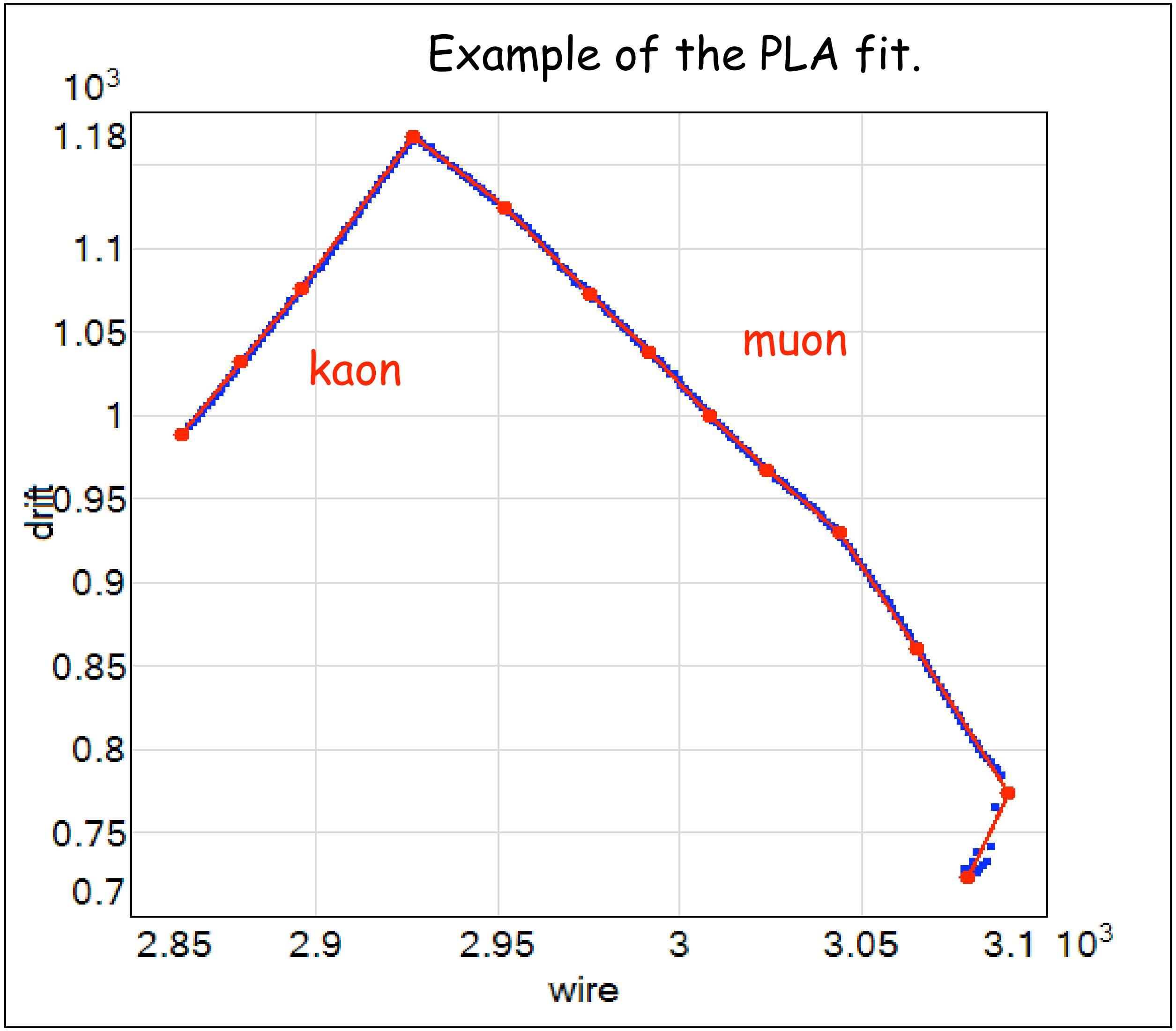
local angle penalty term

segment number k exceeds given ratio $c = k/n$
track hits number: longer tracks usually are more straight

http://www.iro.umontreal.ca/~kegl/research/pcurves/

Polygonal Line Algorithm: short tracks

- Blue points: hits in collection
- Red points /segments: vertex/segments of the PLA fit

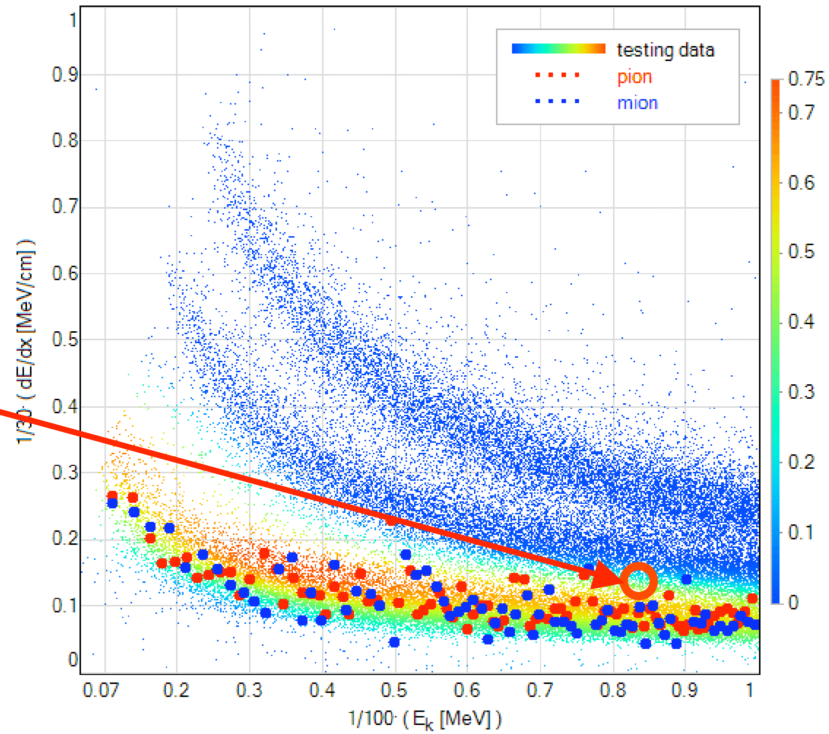


Neural Network particle identification: $\chi 2$

- Particle identification is based on:
  - distance between nearby 3D hits: dx
  - 3D hits and charge deposition : dE/dx
- classify single i^{th} point on the track

$\mathbf{p}_i$: [E_k, dE/dx] $\rightarrow$ $\mathbf{nn}_i$: [P(p), P(K), P(p), P(m)

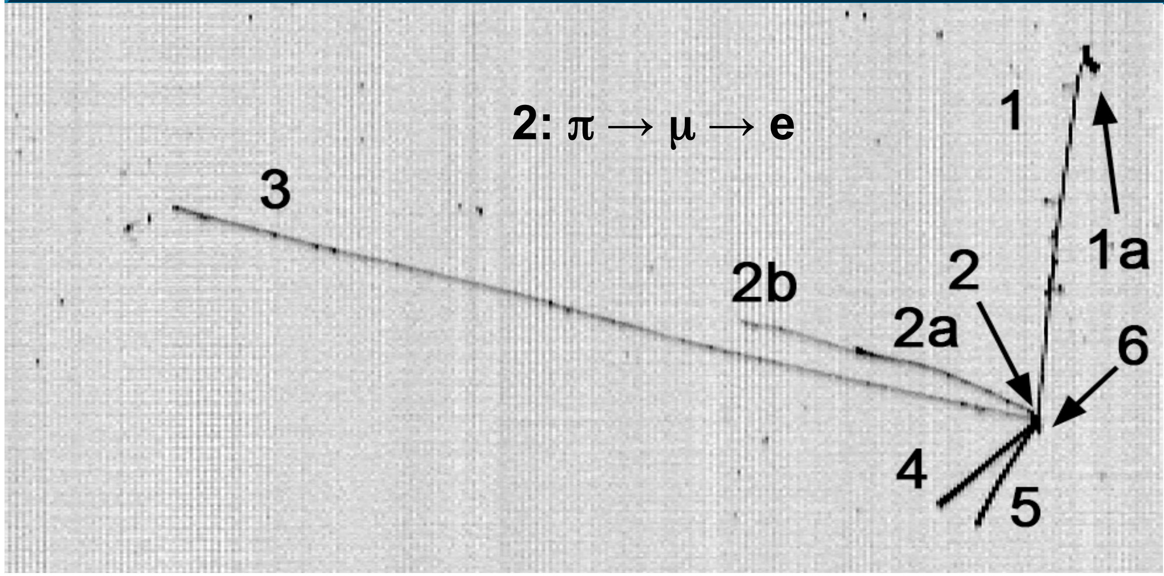
- Average M output vectors for the points
  NN = S($\mathbf{nn}_i$)/M
- Identify track as particle corresponding to max(NN)
- Energy reconstruction with simulation for quenching

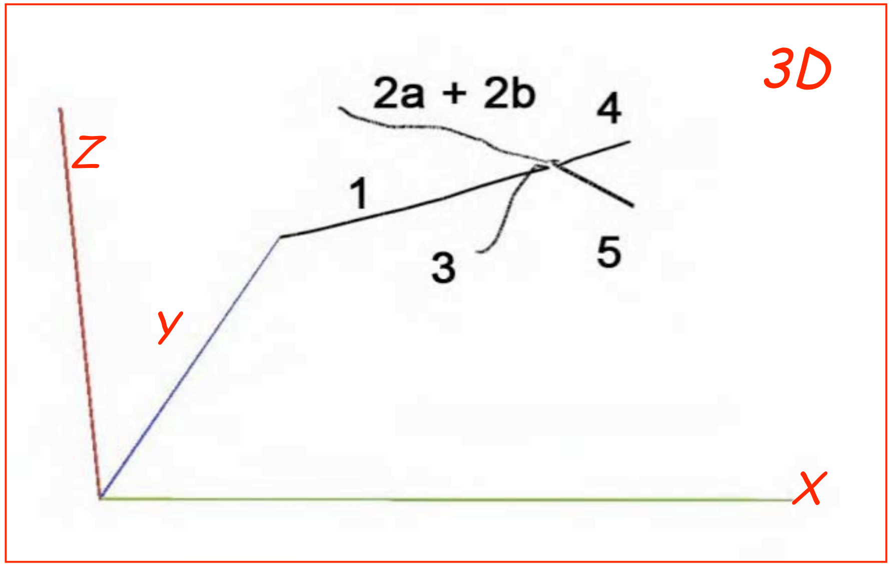


pid / MC	p	K	π	μ	efficiency [%]	purity [%]
p	**481**	4	0	0	99.2	98.0
K	10	**380**	0	0	97.4	99.0
π	0	0	**196**	40	83.1	98.5
μ	0	0	3	**216**	98.6	84.4

Very high identification efficiency for p, k, pion+muon

Run 9392 Event 106

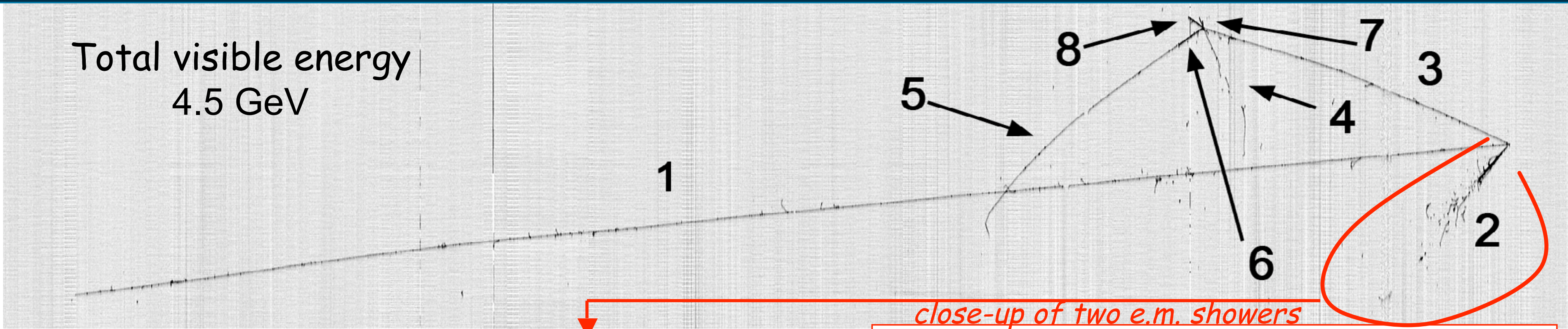




Track	E_k [MeV]	Range [cm]
1 (prob. π, decays in flight)	136.1	55.77
2 **(π)**	26	3.3
2a **(μ)**	79.1	17.8
2b **(e)**	24.1	10.4
3 **(μ)**	231.6	99.1
4 **(p)**	168	19.2
5 **(p)**	152	16.3
6 (?) (merged with vtx)		2.9

- Total deposited energy 887 MeV
- Total reconstructed p 929 MeV/c at about 30° away from the CNGS beam direction

Run 9927 Event 572

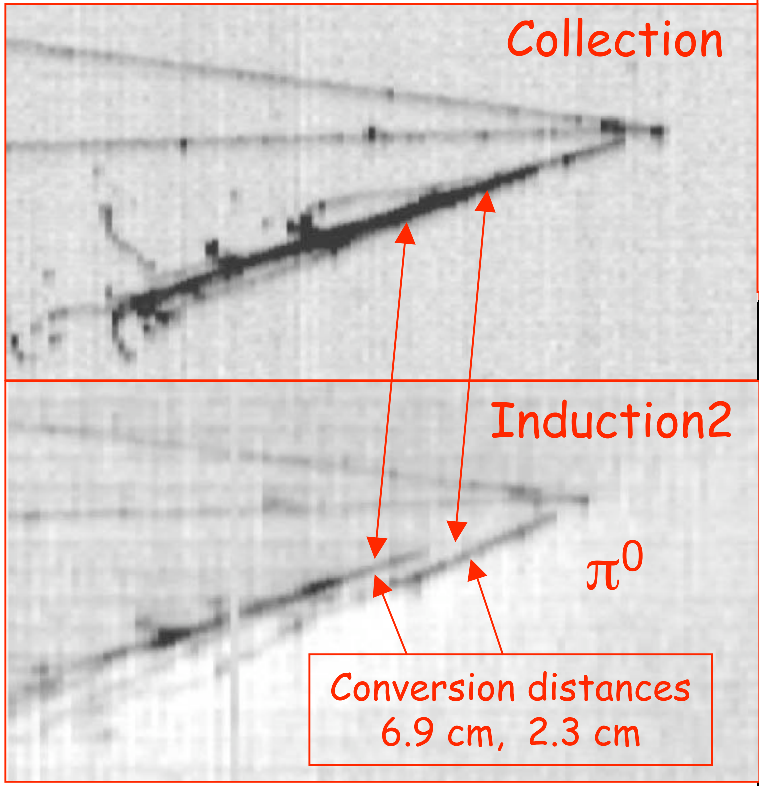


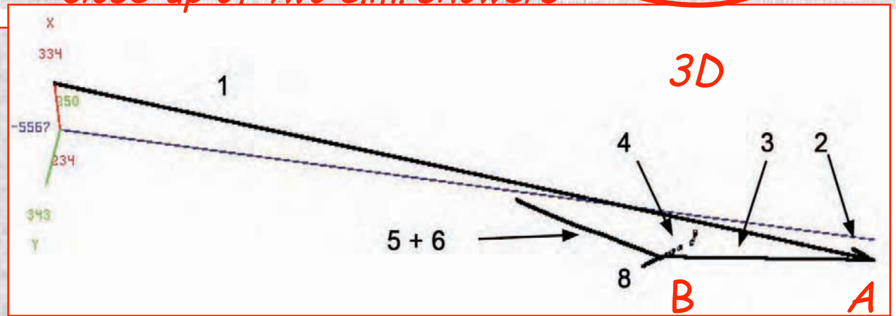
Primary vertex (A):

very long (1), e.m. cascades (2), pion (3)

Secondary vertex (B):

The longest track (5) is a μ coming from stopping **k** (6). μ decay is observed





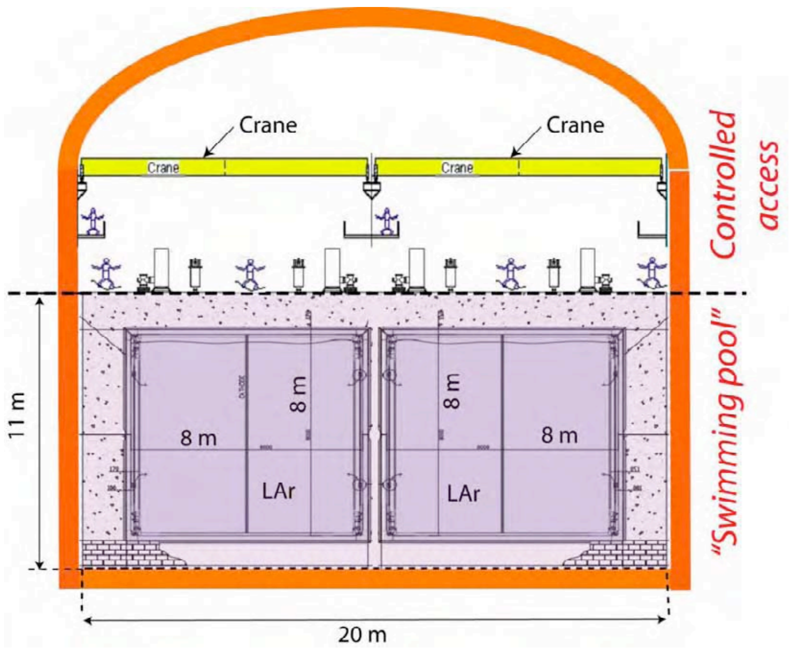
Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

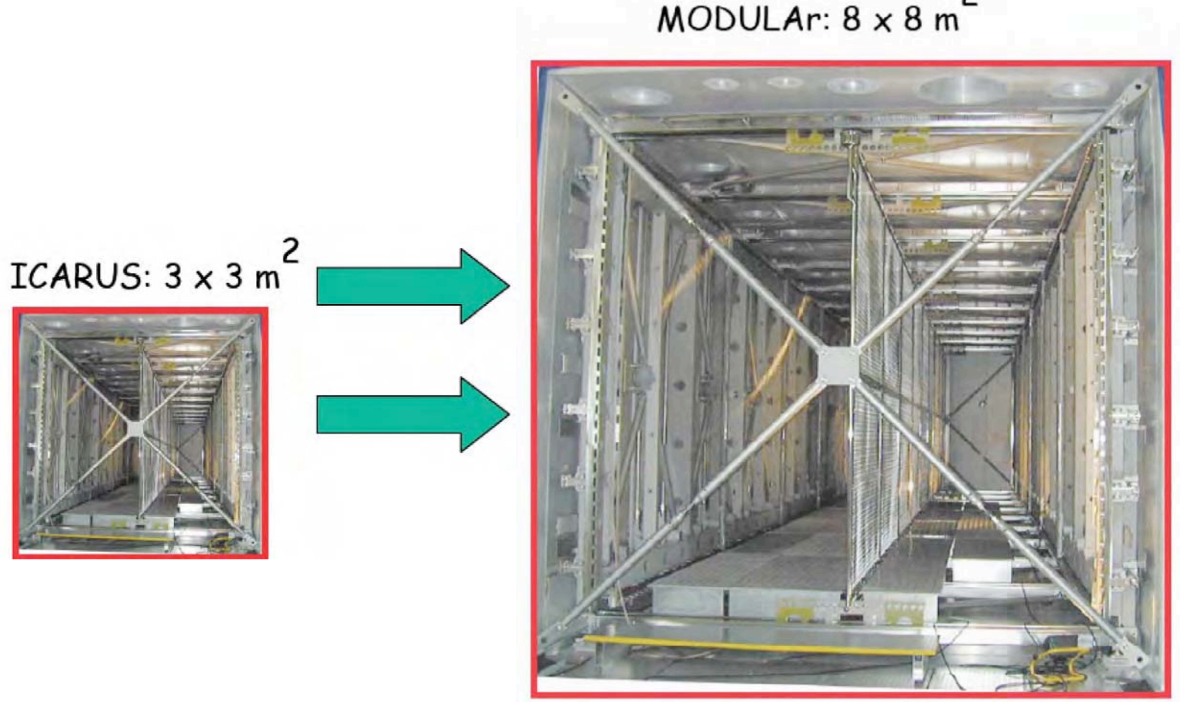
Beyond ICARUS-T600

- The operation of the T600 demonstrates the large number of important milestones which have been achieved in the last several years, opening the way to the development of new line of modular elements, which may be progressively extrapolated to the largest conceivable LAr-TPC sensitive masses.
- Based on the T600 experience, the ICARUS collaboration has now proposed a next generation LAr-TPC in tens of kt scale: the MODULAr project. (*Astroparticle Physics 29 (2008) 174)*
- The new detector, *using the present CNGS beam off axis with several 5 kton* units will maintain the majority of components developed with industry for the T600.
- This detector might be easily upgraded in the far future to a larger scale, depending on the potential physics goals.

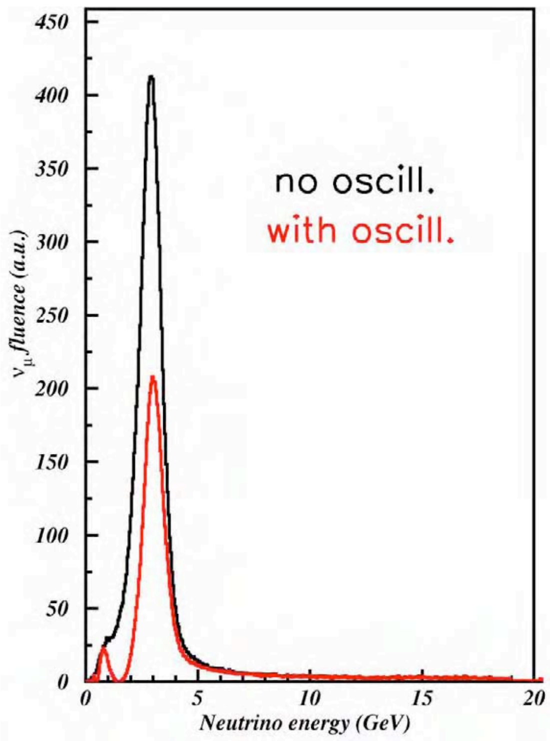
The MODULAr detector

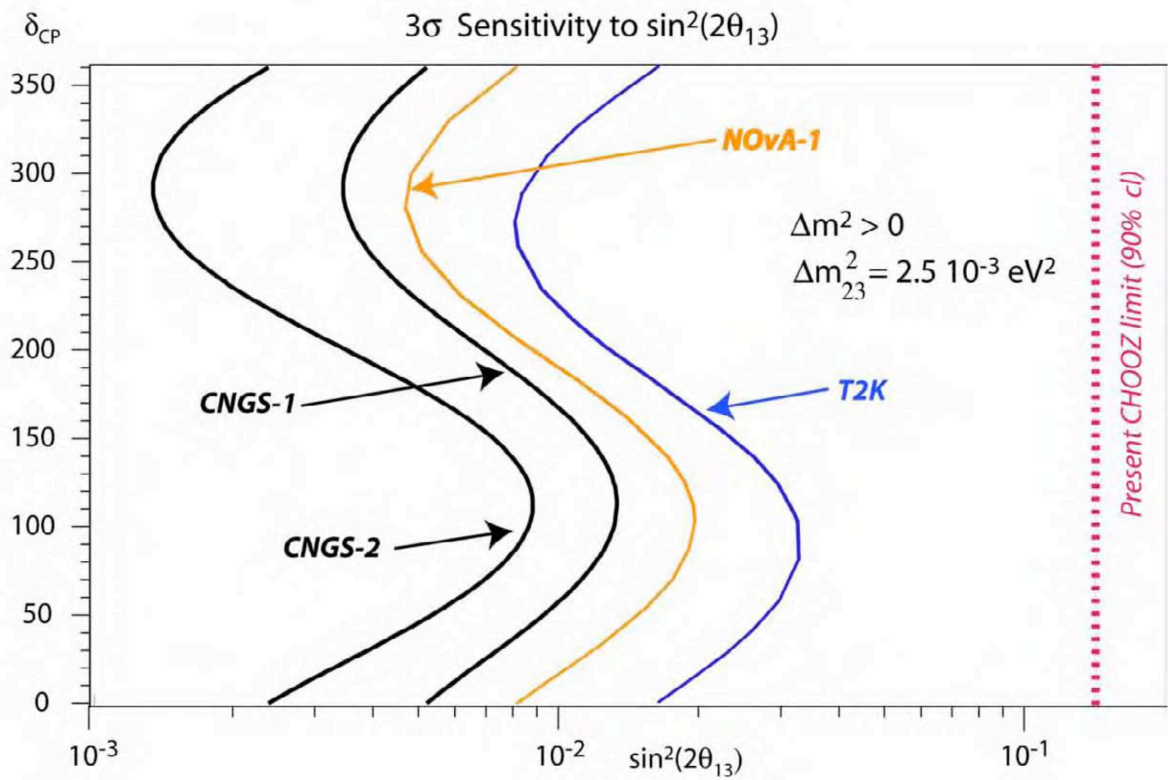
- MODULAr will be initially composed by four identical modules located in a new shallow-depth cavern, 10 km off axis from existing CERN/CNGS beam.
- Each module is a scaled-up version of the T600 (x 2.66^3):
  - 8 X 8 m^2 cross section and about 60 m length
  - LAr active mass: 5370 ton
  - 4 m electron drift (2.66 ms), E_{drift} = 0.5 kV/cm, H.V.: -200 kV
  - 3-D imaging similar to T600 but 6 mm pitch (three planes, ~50000 chs)





MODULAr Sensitivity to θ_{13} and δ_{CP}

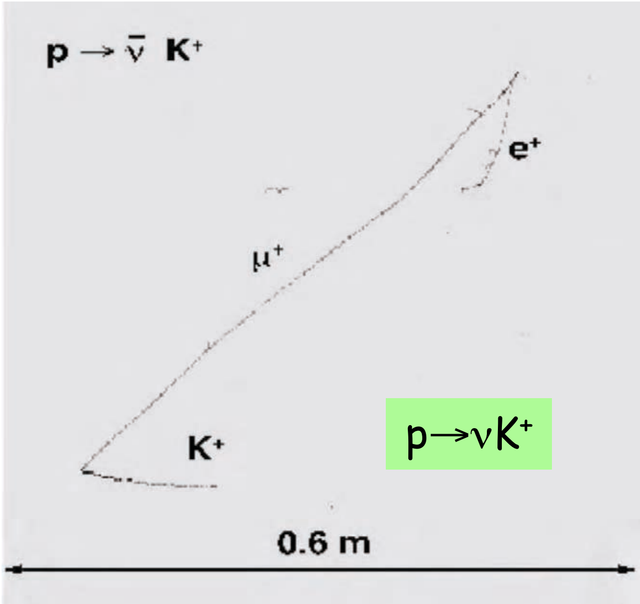


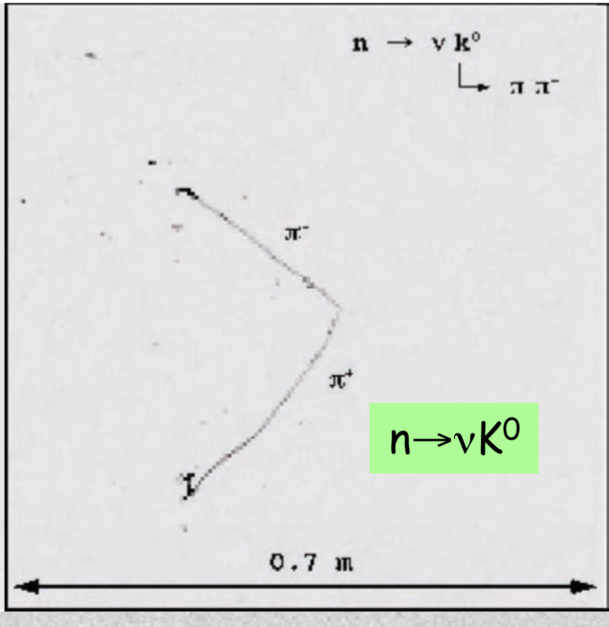


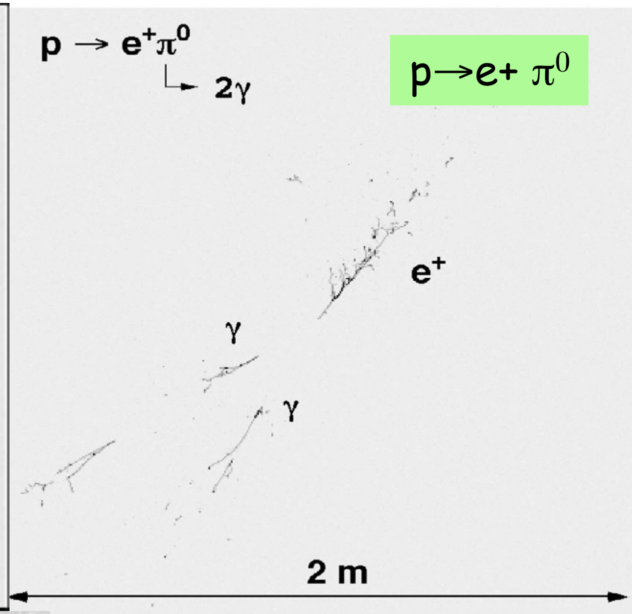
Event rates in MODULAr
(20 kt, 5 y, 1.2 10^{20} pot/y, $\sin^2(2\theta_{13})$=0.1)
5% beam systematics. $\Delta E/E$ = 15%

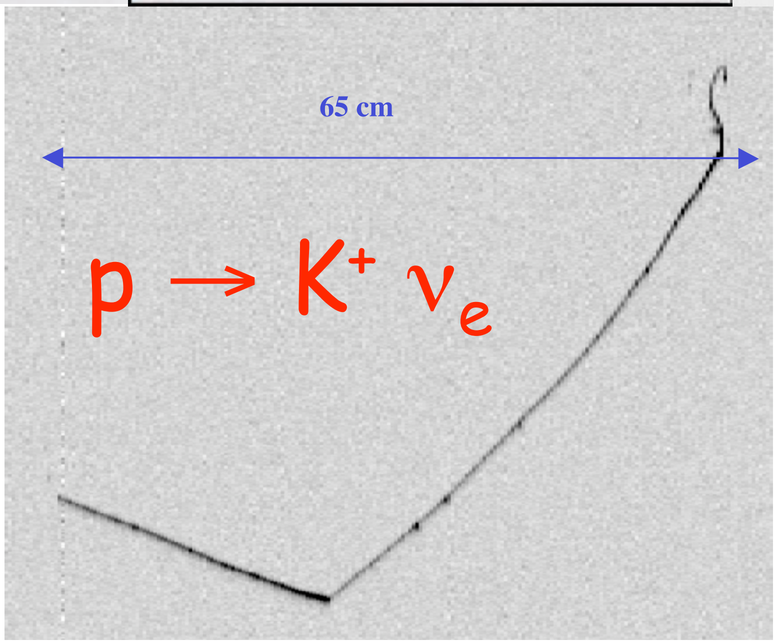
ν_μ CC	e bkg	Signal	S/$\sqrt{(bkg)}$
5700	28	250	47

Nucleon decay : single event capability





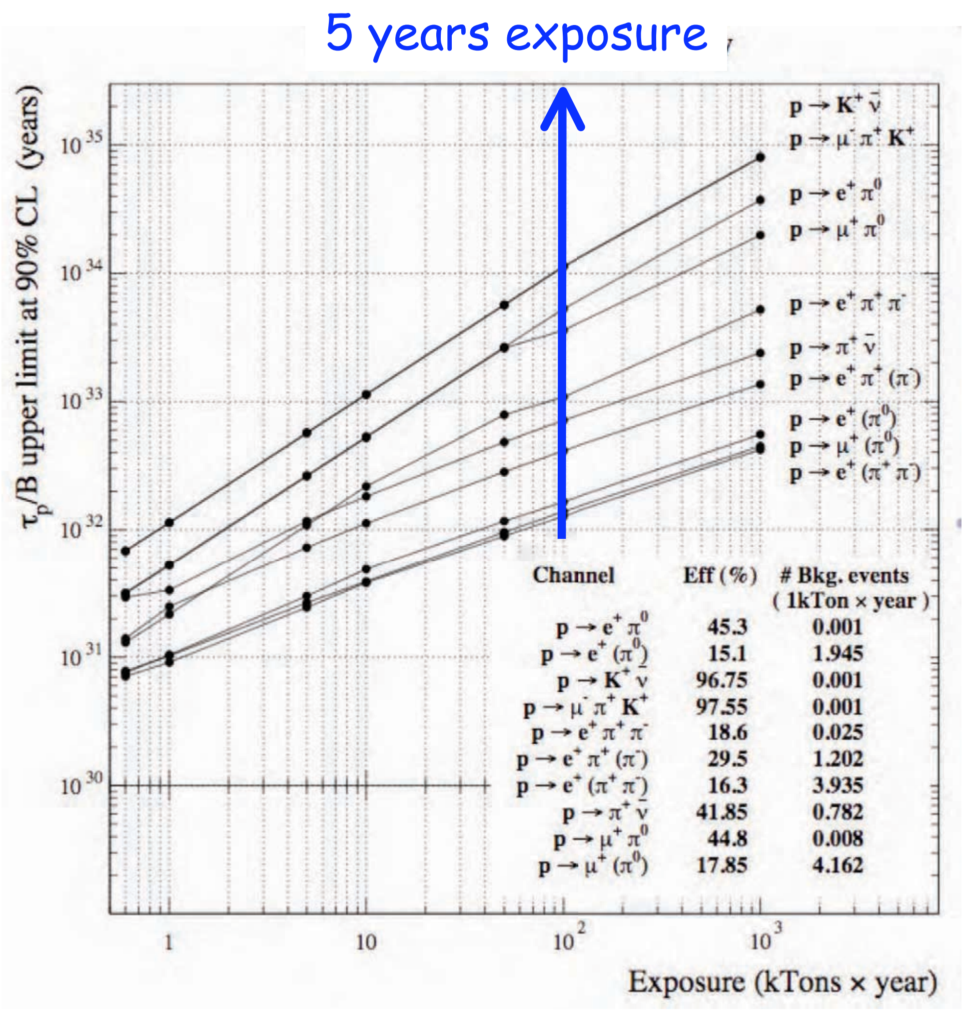




Nucleon decay expectations

- LAr-TPC provides a much more powerful bkg rejection w.r.t. other techniques. It can perform a large variety of exclusive decay modes measurements in bkg free mode.
- With *1.2 10^{34} nucleons*, MODULAr is well suited for channels not accessible to Č detectors due to the complicated event topology, or if the emitted particles are below the Č threshold (e.g. *K^+*)

Channel	*90%CL-5y*	*(pdg 90%CL)*
$p \rightarrow \nu\, \pi^+$	$4.4\ 10^{33}$	$(2.5\ 10^{31})$
$p \rightarrow \mu^- \pi^+ K^+$	$1.1\ 10^{34}$	$(2.5\ 10^{32})$
$n \rightarrow e^- K^+$	$1.3\ 10^{34}$	$(3.2\ 10^{31})$
$n \rightarrow \mu^+ \pi^-$	$6.0\ 10^{33}$	$(1.0\ 10^{32})$
$n \rightarrow \nu\, \pi^0$	$4.4\ 10^{33}$	$(1.1\ 10^{32})$



New physics with the T600 detector.

- According to expectations, the present exploitation of ICARUS in the Hall-B of LNGS will be carried out during 2011 and 2012.
- Neutrinos have been the origin of an impressive number of "Surprises". The sum of the strengths of the coupling of different ν is very close to 3, but its number may be altered by the additional presence of other "sterile" neutrinos.
- It is only because the masses of known neutrino species are so small, that their contribution to the Dark Matter of the Universe can be neglected. The additional presence of *massive sterile neutrinos* may for instance contribute to Dark Matter.
- The LSND and the MiniBooNE experiments have indicated the presence of anomalies, so far unexplained.
- The novelty of our technology is offering other interesting alternatives with a refurbished ν beam at the CERN-PS.

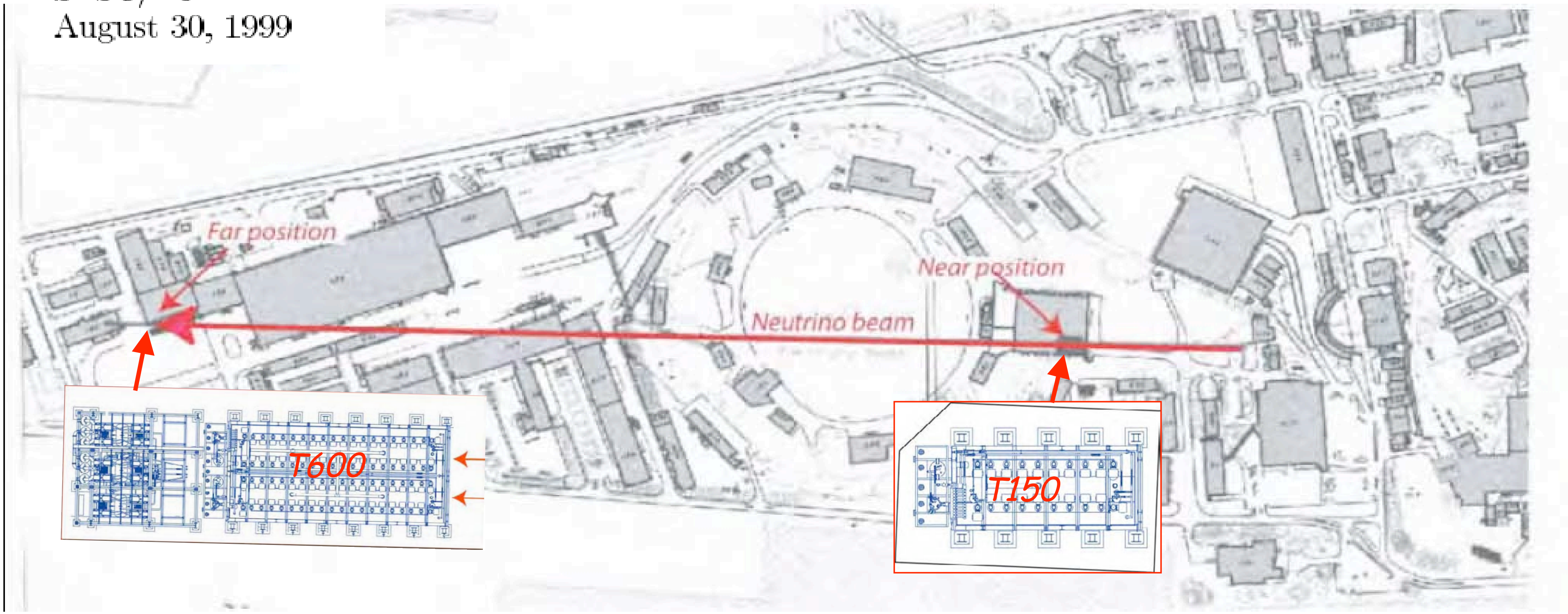
A dual LAr detector at different distances at the CERN-PS

- The recent results at Fermilab open major questions, some of which in apparent agreement with the initial LSND puzzle.
  - MINIBOONE introduces other significant differences with respect to the standard neutrino expectations.
  - MINOS is also hinting at some anomalies which could be explained by sterile neutrino, CPT or by something else.
  - Apparent disagreement between Gallium+Bugey (CPT ?).
- The LAr-TPC may be the solution of these puzzles: a novel search is proposed after the success of ICARUS technology.
- Our proposal is based on two strictly identical LAr-TPC detectors observing the ν_e signal both for $\bar{\nu}_\mu$ and ν_μ in the Near and Far positions, the first with ≈ 150 tons at 127 m, the second with ≈ 600 tons (T600) placed 850 m away. Cross sections and experimental biases cancel out in the comparison.

Two detectors at the PS neutrino beam

CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION
AT THE CERN PS



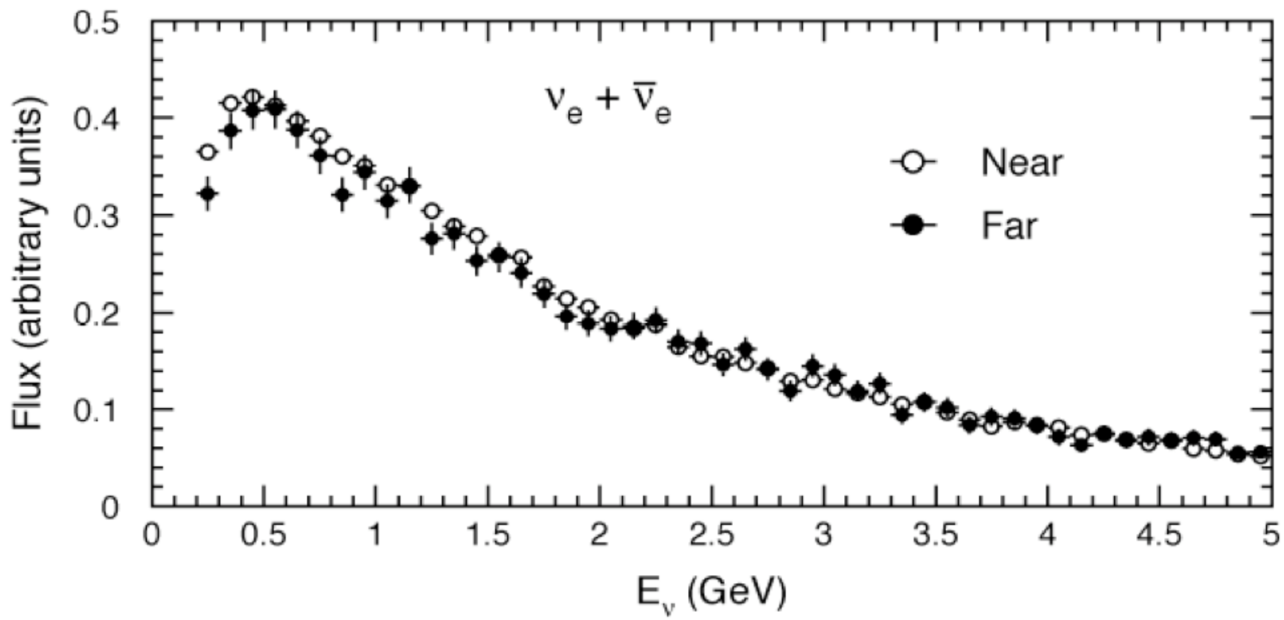
Two positions are foreseen for the detection of the neutrinos

The far (T600) location at 850 m from the target: L/E ~ 1 km/GeV;

The new location at a distance of 127 m from the target: L/E 0.15 km/GeV

Advantages of a dual detector in real time

- *In absence of oscillations*, apart some beam related small spatial corrections, the two spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparison.
- Therefore an exact, observed proportionality between the two ν_e spectra implies directly the absence of neutrino oscillations over the measured interval of L/E.

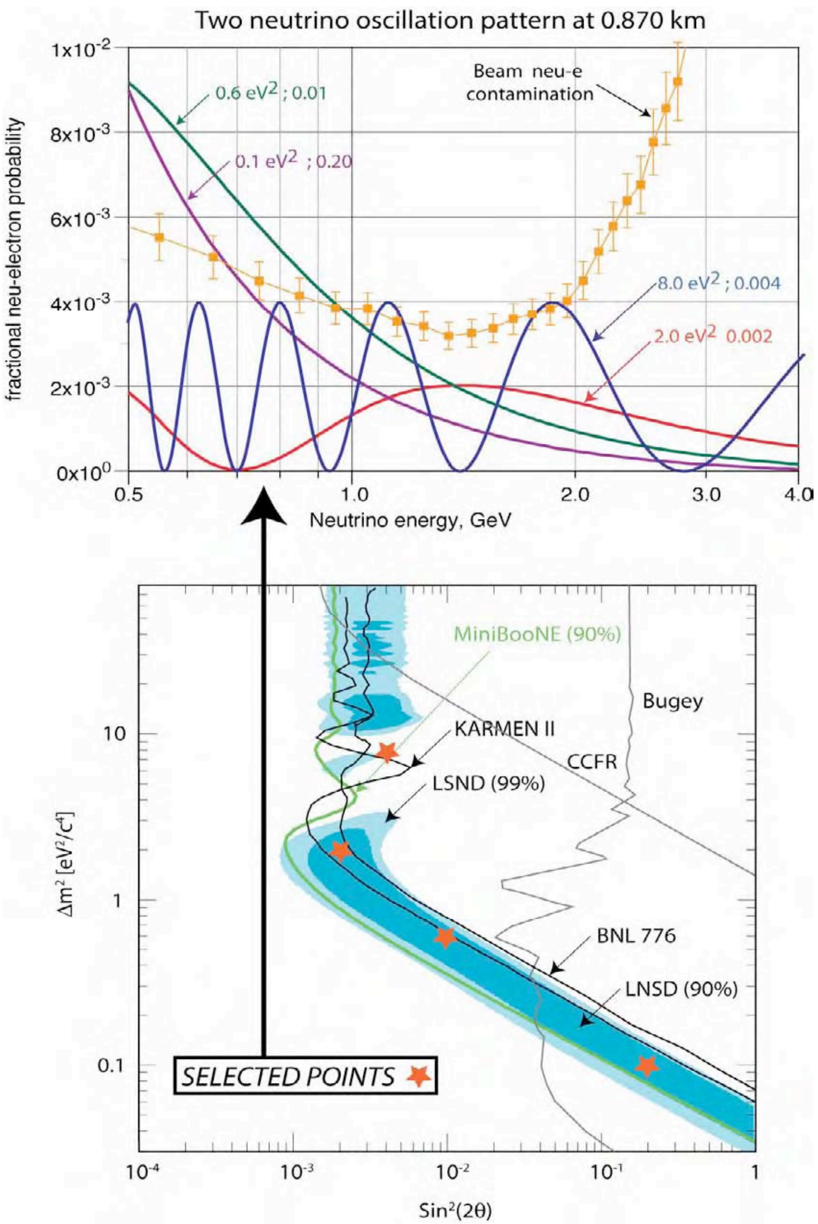


(arXiv:0909.0355)

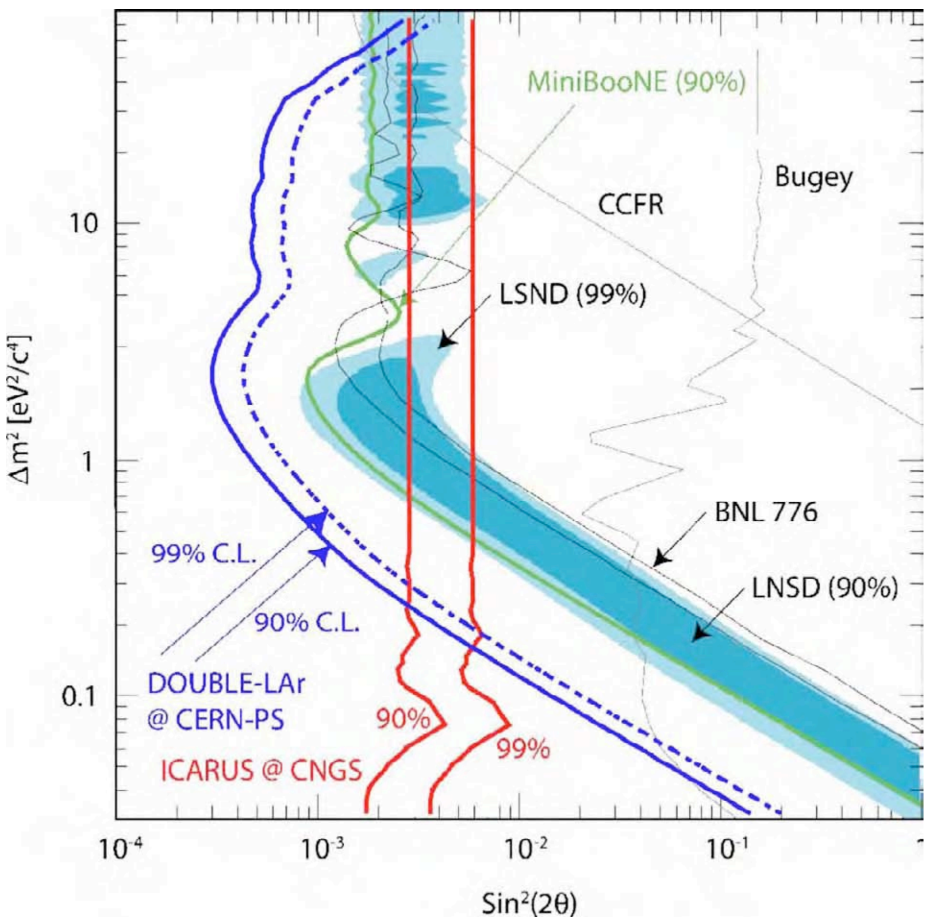
Perfect identity between the near and far positions, dominated by the k-decay spectra

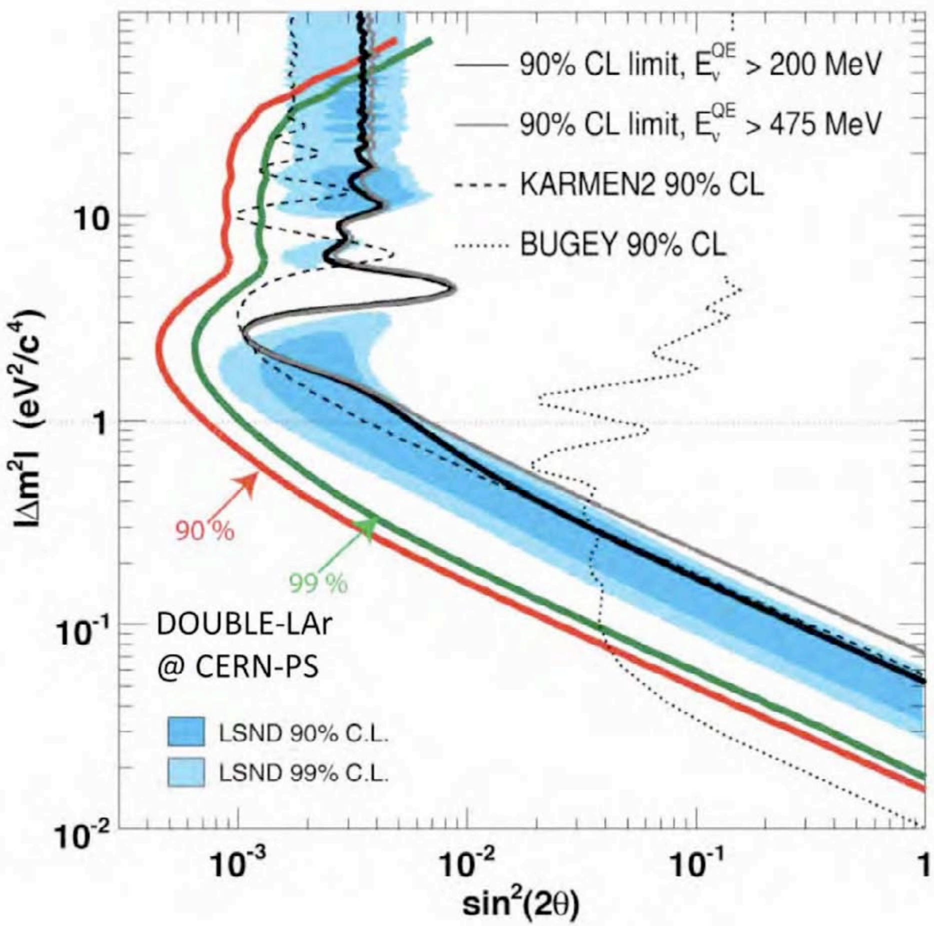
Determination of both the Δm^2 and $\sin^2 2\theta$ values

- It appears that the present proposal, unlike LNSD and MiniBooNE, can determine both the mass difference and the value of the mixing angle.
- Very different and clearly distinguishable patterns are possible depending on the values in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsic ν-e background due to the beam contamination is also shown.
- The magnitude of the LNSD expected oscillatory behaviour, for the moment completely unknown, is in all circumstances well above the backgrounds, also considering the very high statistical impact and the high resolution of the experimental measurement.



Comparing sensitivities *(arXiv:0909.0355)*





Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for 2.5 10^{20} pot and twice as much for anti-neutrino (right) . The LSND allowed region is fully explored both for neutrinos. The expectations from one year of at LNGS are also shown.

Thank you !